Chipseal cracking
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An important note for the reader

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Abbreviations and acronyms

AADT	annual average daily traffic
AC	asphalt concrete
ASTM	American Society for Testing and Materials
HAPAS	Highway Authorities Product Approval
LTPP	long-term pavement performance
PCI	pavement composite index
RAMM	Road Assessment and Maintenance Management (Database)
SH	state highway
Transport Agency	New Zealand Transport Agency
vpd	vehicles per day

Contents

Executive summary

Cracking is an important failure mode for chipseals in New Zealand and can lead to water entering and damaging the underlying pavement, but despite the importance of cracking very little research has been undertaken to explore the phenomenon in New Zealand or elsewhere.

This research, carried out in 2014/2015, investigated various aspects of the problem:

Causes of cracking: The key question is how do cracks form in the seal? The hypothesis investigated was that seals fatigue crack in an analogous way to asphalt mix, ie pavement deflection is the dominating factor for crack formation and growth (rather than simply bitumen hardening).

Crack repair and mitigation techniques: Individual crack sealing (ie without resealing the whole surface) is in some cases a cost-effective way of repairing seal cracking. The methods used for seal crack repair were reviewed and guidelines were developed to form the basis of a performance-based specification.

Modelling crack initiation, growth rates and maintenance practices: The rate of crack initiation and growth rate in seals was analysed using data from the long-term pavement performance sites. The potential for using this data to develop a tool to understand the implications of deferring crack repair or resealing was explored.

Causes of cracking

The fatigue cracking behaviour of laboratory prepared chipseal beams and beams cut from field samples was studied using a four-point bending beam, test method. Tests were conducted at 10Hz and at strain levels of 100 to 1,000$\mu\varepsilon$; failure was defined as the number of cycles taken for the flexural modulus to fall to 50% of the initial value.

The chipseal beams were found to fail through fatigue cracking at 5ºC but were not able to be tested at higher temperatures due to deformation of the specimens over the period of the test. The fatigue lives were compared with literature data for typical New Zealand asphalt surfacings. Chipseal fatigue lives at 5ºC were found up to eight times greater than those of estimated values of asphalt under the same loading conditions. These are preliminary findings and need to be confirmed through more extensive testing, but the higher seal fatigue lives are consistent with the high binder content in multi-layer chipseals compared with asphalt and the lower initial moduli. The effect of rest periods to allow self-healing was not investigated in the current project but would be expected to be significant in seals due to the thick binder films present. This would tend to further increase the relative fatigue life of chipseals compared with asphalt.

Bitumen oxidised to an equivalent field age of approximately four to five years actually resulted in a slight improvement in chipseal fatigue life at 5ºC. This observation together with previous work on binder hardening in New Zealand seals suggests that oxidation is not the dominant factor in seal cracking. This finding and the high fatigue lives predicted for seals suggest that cracking occurs due to very high, localised deformations. Such deformations may arise through weak basecourse patches formed during construction or more likely, from water damage arising from leaking seals. In multi-layer seals water ingress can also weaken the seal structure through stripping of the bitumen from the aggregate at the base of the layer. Thus it seems likely that in many cases seal cracking and flushing are directly related.

Crack repair and mitigation techniques

Practice guidelines and performance specification concepts for the crack repair of chipseals have been prepared.

A performance-based specification similar to NZ Transport Agency pilot specification P25 (NZ Transport Agency 2012) for high-friction surfacings is suggested, in which a minimum performance level is set for the duration of a two to three year defects liability period.

Satisfactory performance would be assessed in terms of:

- the absence of significant bleeding or bitumen pick-up onto tyres and tracking
- the absence of potholes on a repaired crack
- the percentage of repaired crack length that had failed, defined as:
  - reopening, spalling or widening of repaired cracks
  - loss of adhesion of the sealant bandage to the surface.

In addition some basic physical test requirements have been suggested that would be set to exclude obviously unsuitable materials. These requirements would be based on overseas specifications (which many proprietary sealant materials used in New Zealand already meet).

Modelling crack initiation and growth rates

Data from the LTPP sites shows that overall, the average number of cracks initiated per site increased approximately linearly from the time of crack initiation. The data for all sites can be summarised as below:

Transverse crack growth rate: Number of cracks/km of road = 0.4773(years since initiation) +5.7

Longitudinal crack growth rate: Number of cracks/km of road = 0.4181(years since initiation) +7.2

Alligator crack growth rate: Number of cracks/km of road = 0.4845(years since initiation) +1.7

For the three different crack types investigated for both state highways and local authority roads the average annual increase in crack length for any given crack is approximately half the crack length, so as the crack grows the rate of crack growth in mm/year increases.

Combined crack length growth: Crack growth mm/year = 0.4566*crack length +334mm

A brief analysis was carried out for two sites that appeared to show an approximately three-year lag between crack initiation and pothole formation but more extensive analysis is needed before any general conclusions can be drawn.

Cracking maintenance practices

Experienced engineers will always highlight the importance of keeping surfaces watertight in order to ensure good performance from granular pavements. No finding in the research suggested any difference to this philosophy, with the research highlighting the importance of watertight surfaces and good drainage. The results suggested that pavements deteriorated 30% faster with inadequate drainage including surface drainage.

The analysis also considered both field programmes and optimal programmes in order to determine some practical guidance for better decision making when considering defects such as cracking and rutting. One of the stand-out observations was that field staff would surface sections at lower crack percentages compared with the rehabilitation sites that normally had much higher crack percentages. The crack percentages for the optimised programme did not differ significantly between rehabilitation and resurfacing treatments. Yet, it was evident that the rehabilitation sections had a combination of cracking and rutting present.

The optimal programme was further investigated in order to establish typical cut-off points where certain treatments were triggered on the basis of defects such as cracking. This could not be established because there are a significant number of factors involved with the optimal timing of treatments. There would also be an endless amount of combinations of defects that would determine the optimal timing of treatments. Optimal treatment timing is best determined by software applications specifically developed for this function. It cannot be replaced by simple rules. In addition to that it is recommended that field inspections consider the combination of defect in deciding on the appropriate treatments rather than considering isolated treatments individually. For example a section containing only cracking may benefit from a resurfacing treatment, whereas a cracked section that also shows a significant rut rate may be more appropriate for rehabilitation.

Abstract

The fatigue cracking behaviour of laboratory prepared chipseal beams and beams cut from field samples was studied using a four-point bending test method. Preliminary results indicate that chipseal fatigue lives at 5ºC are up to eight times greater than those of estimated values for asphalt mix under the same loading conditions. The results suggest binder oxidation was not the dominant factor in seal cracking and that cracking in the field may be primarily due to very high, localised deformations. Such deformations may arise through weak basecourse patches formed during construction or more likely, from water damage (to both the basecourse and seal structure itself) arising from leaking seals.

Data from long-term pavement performance sites show that overall, the average number of cracks initiated per site increased approximately linearly from the time of crack initiation. The average annual increase in crack length is approximately half the crack length, so as the crack grows the rate of crack growth in mm/year increases. A brief analysis was carried out for two sites that showed an approximately three-year lag between crack initiation and pothole formation.

The report proposes practice guidelines and the outline of a performance-based specification for the crack repair of chipseals.

1 Introduction

In a recent analysis of chipseal performance, about 20% of seals on the New Zealand state highway network failed through cracking (Towler et al 2010), second only to flushing as a reason for resealing. Cracks in the seal must be repaired to prevent water entering and damaging the basecourse. Despite the importance of cracking very little research has been undertaken to explore the phenomenon.

The objectives of this research, carried out in 2014/2015, were to:

- investigate the causes of cracking in chipseals
- determine the rates of crack progression and estimate the effects of delaying maintenance on pavement life
- determine if seals that fail by cracking have a shorter life than those that fail by flushing
- develop practice guidelines and a specification concept for crack repair techniques.

1.1 Causes of cracking

The key question is how do cracks form in the seal? The hypothesis investigated was that seals fatigue crack in an analogous way to asphalt mix, ie that pavement deflection is the dominating factor for crack formation and growth (rather than simply bitumen hardening through oxidation). Understanding the key physical factors involved in cracking, will help focus attention on the key construction and maintenance practices that need to be improved in order to minimise seal cracking.

Although cracking of chipseals has long been recognised as a failure mechanism, a search of the literature did not find any publications dealing with the detailed physical processes involved in seal cracking. Specifically factors affecting crack initiation and propagation in seals, how the level of pavement deflection affects crack propagation and crack development affects pavement deterioration, do not appear to have been studied in detail.

Outside of Australia, New Zealand and South Africa cracking in chipseals is infrequently mentioned in research into chipseal performance (Boyer and Ksaibati 1998. Emphasis is placed instead on early life failure due to bleeding or especially chip loss and how it is related to emulsion curing rates (eg Howard et al 2011). For example researchers in the USA in a series of papers on the development of a performance-based bitumen specification for seals do not consider cracking as a failure mode in seals (Barcena et al 2002; Walubita et al 2004; Hoyt et al 2010). This may reflect the fact that in the USA seals are typically used as a pavement preservation measure between asphalt surfacings or rehabilitation (Gransberg and James 2005) and typically only have lives of only five to six years – not long enough for cracking to develop. Work in South Africa studying the performance grading of seal binders lists fatigue cracking and thermal cracking as failure modes for seals but does not discuss the underlying causes (Bahia et al 2008).

1.2 Crack repair and mitigation techniques

Individual crack sealing (ie without resealing the whole surface), is in some cases a cost-effective way of repairing seal cracking. The methods used for seal crack repair were reviewed and guidelines that could form the basis of a performance-based specification were developed.

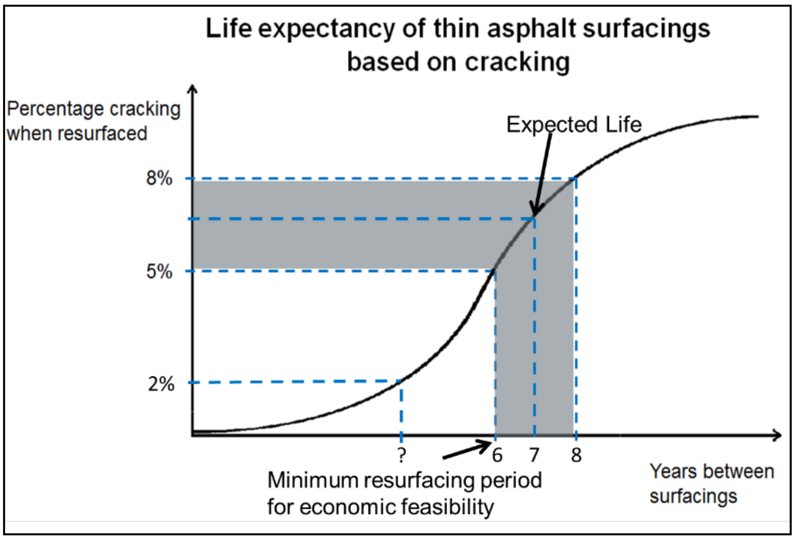
1.3 Modelling crack initiation, growth rates and maintenance practices

In combination, cracking and flushing contribute to approximately 70% to 80% of resurfacing on New Zealand roads. Flushing, being a safety concern due to loss in macro-texture is often viewed as non-negotiable from a maintenance perspective. Cracking on the other hand may be tolerated if only a minor extent of cracking is observed. Isolated cracked areas may be treated using crack sealants and when extensive cracking is observed engineers will consider a full width surface seal. Therefore if savings in maintenance are to be achieved, roads re-surfaced as a result of cracking may be primary candidates for deferral. This research addressed a number of questions on these issues.:

- What are the actual yearly rates of crack initiation and growth rate in seals and how rapidly does pavement damage occur as a result?
- What is the proportion of resurfacing carried out as a result of flushing versus cracking?
- Under what circumstances would the deferral of resurfacing be an option given different degrees of cracking?
- What are the life-cycle cost implications related to deferring the resurfacing of cracked surfaces? It may be possible to save money by deferring resurfacing but ultimately costs may be significantly more in the future if all these sections have to be rehabilitated.

As an example of the last point, similar work has been completed on the life-cycle aspects of thin asphalt surfaces (Foulkes and Jones 2012). One of the main findings from this research was that the performance of the surface was a strong function of the cracked status before resurfacing. In many cases, thin asphalt surfaces did not reach the expected life that is used as the economic justification for applying these surfacings (refer to figure 1.1).

Figure 1.1 Life expectancy of asphalt surfaces as a function of previous cracking



Source: Foulkes and Jones (2012)

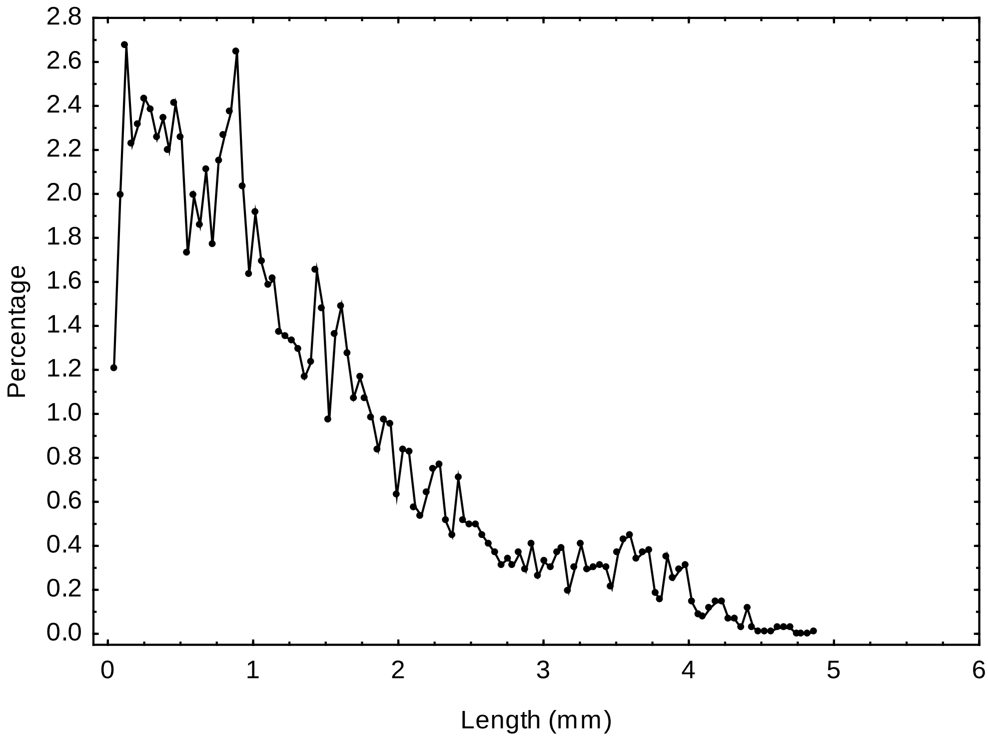
2 Causes of cracking in chipseals

2.1 Crack formation and propagation mechanisms

The mechanisms that give rise to cracking in asphalt mixes can also potentially cause cracking in chipseals. Transverse cracks may be caused by volume changes of the underlying pavement resulting for example from shrinkage of cement stabilised basecourse. Cracking due to diurnal thermal expansion and contraction of the seal is not common in either chipseals or asphalts in New Zealand because of our mild climate and relatively small daily temperature changes. However as for asphalt mix, reflective cracking of existing underlying cracks or moving joints, seal edges or (on local authority roads) underground services may also result in cracking in chipseals. Reflective cracking has been studied by Tredrea (1986) and Wilson et al (2009).

The above cracking processes result from rapid or larger than normal seal movement and cause rupture of the film between chips. Compared with asphalts, bitumen film thicknesses in seals are on average much greater than asphalts. Median film thicknesses in the vertical direction for a grade 3 seal (average least dimension of 9mm) with bitumen application rates of 1-2Lm^{-2} and varying chip application rates ranged from 1.6 to 3.6mm. Values ranged up to 5mm as shown in figure 2.1 (Herrington and Henderson 2004), and calculations were made by measuring the film depth in seal cross sections from the surface or between aggregate particles at 40µ intervals along the x-axis. Film thicknesses in asphalts are in the order of microns in comparison and are much more narrowly distributed than in seals (Elseifi et al 2008).

Figure 2.1 Bitumen film thicknesses normal to the surface for a grade 3 chipseal. The x- axis shows the film thickness and the y- axis shows the percentage of the total number of film thickness measurements



Source: Herrington and Henderson (2004)

The range of film thicknesses in seals means deformations of the layer under traffic that would result in film rupture in an asphalt mix will only impact on a small proportion of the films between chips. Cracks formed in a thin part of a film may only propagate a small distance before striking a much thicker region of the film where the deformation can be absorbed without rupture. The thicker binder films also offer more opportunity for self-healing.

For similar-sized deformations chipseals should be less susceptible to cracking than asphalt. Although at a given strain level, brittle failure of the thicker films in chipseals may be less likely than in asphalts, damage may still accumulate due to non-recoverable flow of the binder. The observed macroscopic cracks in the seal surface may thus in effect be a combination of both brittle failure of thin films and ductile failure of thicker bitumen films.

Cracking (eventually becoming alligator cracking), in or near the wheel paths is the most commonly observed form of cracking in chipseals, and is sometimes accompanied by evidence of basecourse fines pumping to the surface indicating that the crack is the full depth of the seal layer (see figures 2.2 and 2.3). Cracking is also very often associated with flushing and is usually localised as illustrated in figure 2.2 (a) and (b) where cracking has only occurred in one wheel path.

Alligator cracking in asphalts is usually attributed to fatigue cracking caused by repeated applications of traffic loads (below the number required to fracture the layer in a single loading event). To investigate the role of fatigue cracking in chipseals experiments were conducted with a four-point bending apparatus using both laboratory prepared and field samples.

Figure 2.2 Chipseal alligator cracking in the wheel path

(a) (b)

(c)

(d)

Figure 2.3 Cracking is very often associated with flushing

2.2 Preparation of fatigue test specimens – laboratory

For the main laboratory study, greywacke aggregates were obtained from Kiwi Point Quarry in Wellington. The aggregates were used to construct beams which simulate multi-layered chipseals for the fatigue life measurements.

The binder used for the lab-based beams was an 80–100 penetration grade bitumen, manufactured from Middle Eastern crudes, comprising both air-blown and propane-precipitated materials, and conforming to the NZTA M/1:2011 specification. Some standard properties of the binder are presented in table 2.1.

Table 2.1 Bitumen properties

Property	Method	Value
Penetration at 5ºC	ASTM D5	10
Penetration at 25ºC	ASTM D5	87
Softening point (ºC)	ASTM D36	47.3
Viscosity at 60ºC (Pas)	AS 2341.2	202
Viscosity at 135ºC (Pas)	AS 2341.3	0.399

The materials were heated at 125ºC before mixing. Each set of beams was manufactured as a slab in a wooden mould with internal dimensions of 450mm long, 450mm wide and 70mm high (figure 2.4). The multilayer seal was constructed using alternating layers of grade 3 and grade 5 aggregates, with approximately 10% of bitumen by weight in each layer. Fines (<150 microns), were added to the binder during mixing at 4%wt. Fines were included to simulate the bitumen mastic found in real seals (Herrington et al 2012). The overall bitumen content was selected to be typical of levels found in real multi-layer seals and that calculated using the standard seal design equations for common, hypothetical sealing situations (Transit NZ 2005; Herrington et al 2012).

The correct amount of binder was weighed into and mixed with the aggregates in a mixer bowl until the surface of every chip was fully covered. The hot mix was poured and spread across the mould one aggregate deep and a rubber roller was used to distribute evenly the coated chips. Baking (silicone) paper was used to prevent bitumen sticking to the roller (figure 2.5). At least three layers of each grade were applied to make up a total thickness of 70mm. The final layer was a grade 3/5 'racked-in' seal (using hot uncoated chip) to try and produce a low texture surface to enable easy mounting in the beam fatigue apparatus (figure 2.6). The final sequence of seals was: 3/5/3/5/3/5/3&5. Sufficient time was spent using the rollers to ensure good packing of the chips into the voids of the underlying layer. A hot air gun was used to keep the assembly hot during compaction. This construction method was adopted after initial attempts to apply the bitumen onto each layer followed by hot clean chip proved unsuccessful as it was not possible to produce repeatable specimens with the chip properly coated with bitumen.

Figure 2.4 A plywood mould with internal dimensions of 450mm x 450mm x 70mm

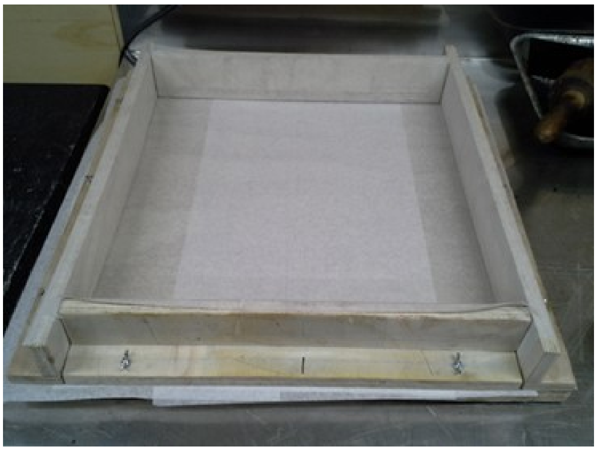
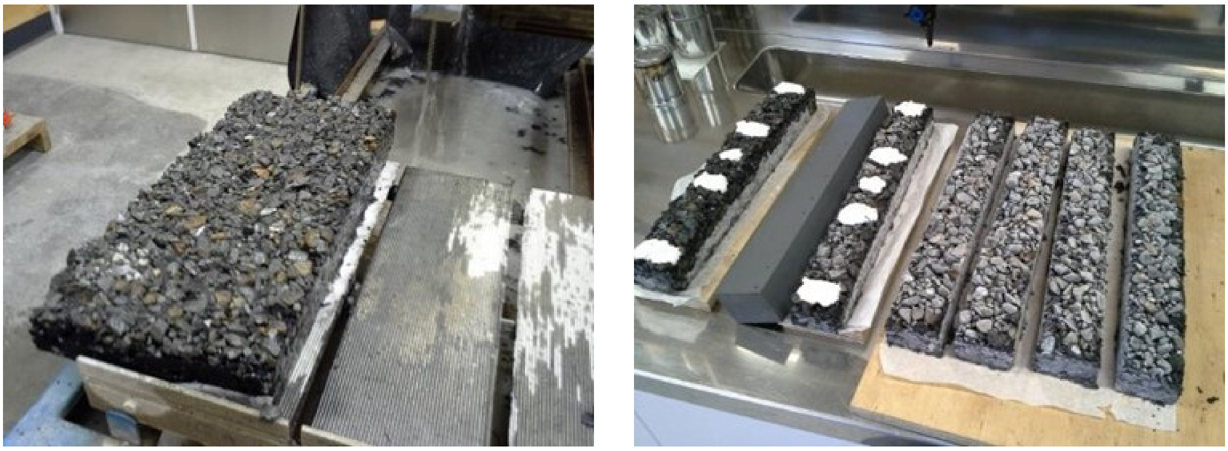


Figure 2.5 Roller compaction of the first layer (left); construction of the subsequent layer (right)

The slab was allowed to cool to room temperature (and any loose chips removed), before being placed in a freezer overnight prior to cutting. Six beams were cut from each slab of chipseal using a water cooled concrete cutting saw. The first six beams were used to test the reproducibility of the beam fatigue experiment. The nominal dimensions of a cut beam were 65mm high, 60mm wide and 400mm long. For the reasons discussed below the beams were later cut on all four sides giving nominal dimensions of 55mm high, 60mm wide and 400mm. For investigation of oxidation effect on fatigue life, the same fabrication procedures were followed for beams using oxidised binders.

Figure 2.6 Application of grade 3 chip (left); application of grade 5 chip to complete the racked- in seal (right)

Figure 2.7 Cutting the slab using a concrete saw (left); test beams (right)

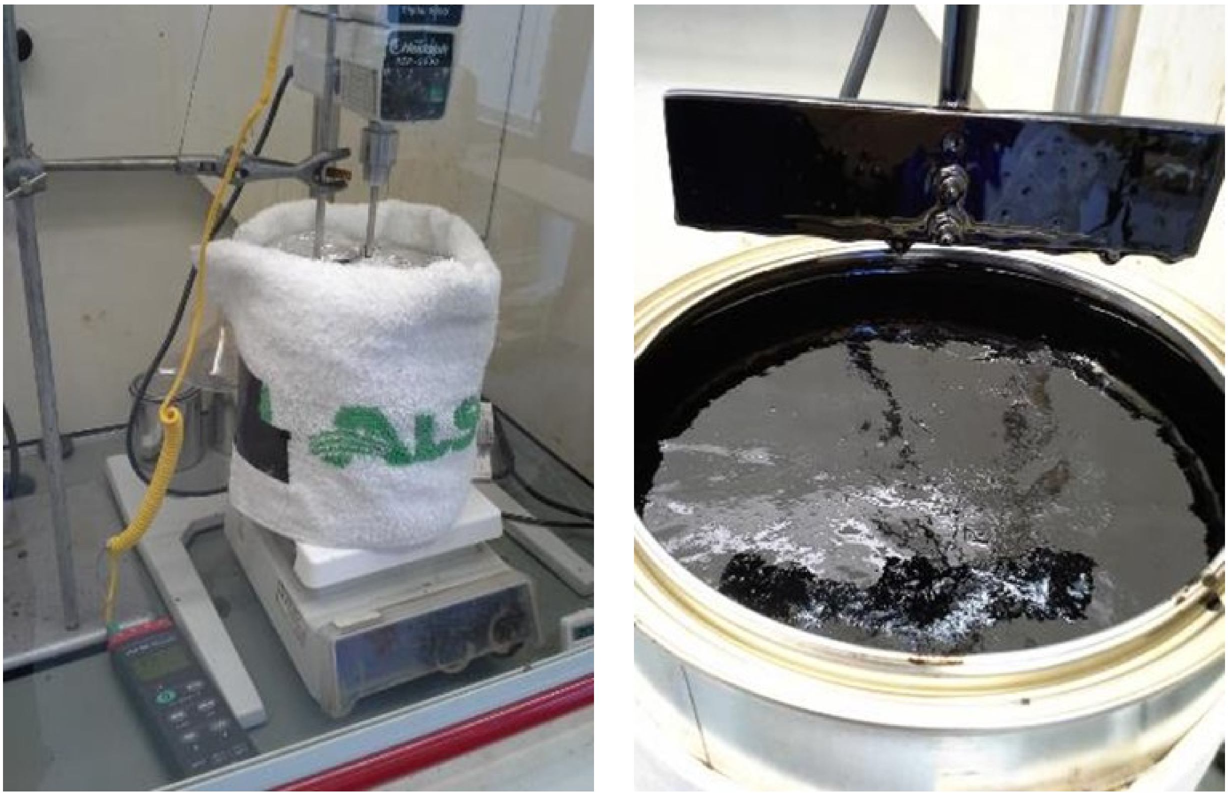


2.2.1 Oxidation

In order to assess the effect of bitumen hardening through oxidation or fatigue, bitumen was oxidised in the laboratory and beams manufactured as described above. Bitumen oxidation was accelerated by vigorous stirring and aeration of the hot bitumen. The vortex created by stirring will disperse oxygen in the bitumen and promote oxidation of the binder. A 4L can of unmodified 80–100 penetration grade bitumen (the same as that used above), was heated on a hot plate at 130ºC and stirred initially using a high-speed mixer (1,200rpm) but to achieve better aeration this was replaced with a high-speed domestic cake mixer. Figure 2.8 illustrates the accelerated aging process as trapped air in the hot bitumen rises to the surface as bubbles once the stirrer is switched off.

The viscosity at 50ºC (0.005s^{-1}) was measured on a dynamic shear rheometer using samples taken intermittently from the oxidation set-up. An approximate equivalent field age of the binder of four to five years was estimated from viscosity data on bitumen films aged outdoors in Lower Hutt for 16 years; see below (Herrington et al 2014).

Figure 2.8 Photo illustrating the oxidation set- up (left); aeration of hot bitumen as a result of stirring (right)



2.2.2 Bitumen extraction

To determine the viscosity of bitumen in the field samples one of the specimens was extracted using dichloromethane. A piece of the chipseal multi-layer of approximately 100g was cut and placed in a beaker. Sufficient dicholoromethane (AR grade) to just cover the sample was added and left, with occasional stirring, for one hour at room temperature, covered and left in the dark.

The solution was decanted into a centrifuge tube and the aggregate washed with 2 x 10ml fresh dicholoromethane. The combined solution was centrifuged for 20 minutes at 2,000 rpm and filtered under vacuum (water pump) through Whatman grade 1 and GFC filter papers (grade 1 paper on the bottom).

Approximately equal portions of the solution were poured onto polished 245 x 340mm stainless steel plates. Stainless steel was used instead of glass to reduce the possibility of selective surface adsorption of polar species. A wide-bladed spatula was used to spread the solution, allowing the solvent to evaporate and leave a thin film of bitumen. After three or four minutes the bitumen was scraped off with a single-sided razor blade. The last traces of solvent were removed by heating the combined bitumen scrapings (about 1–3g) at 100ºC for 60 minutes under >29.9 in Hg vacuum. The samples were stored at -18ºC in a freezer.

2.2.3 Dynamic viscosity by dynamic shear rheometer

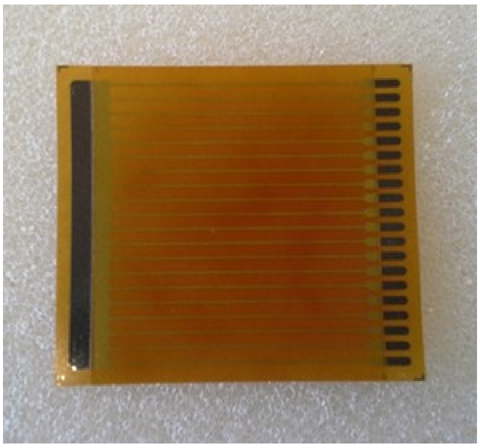
Bitumen viscosity was measured at 50ºC on an AR2000ex (TA Instruments) dynamic shear rheometer using a cone and plate geometry (4º and 25mm in diameter). The extraction procedure as described above has been shown to have no significant effect on the measured viscosity (Herrington et al 2007).

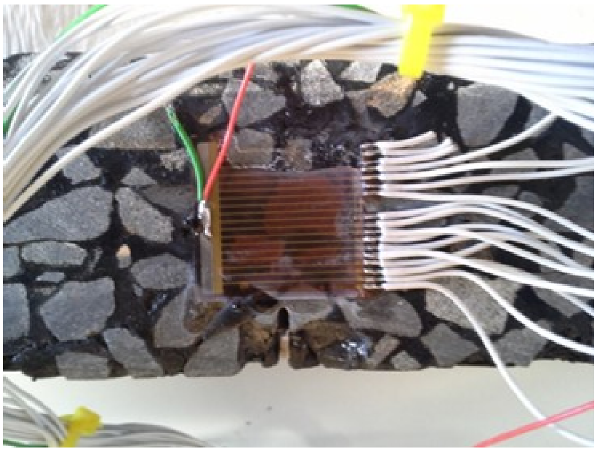
2.2.4 Measurement of crack propagation rate

Crack propagation in chipseal beams was measured using a specialist gauge (HBS model 1-RDS-20), which is mounted on the side of the beam with an epoxy-based adhesive. The gauge (figure 2.9) consists of 20 parallel wires, spaced at 1mm intervals), with individual contacts on one end and a joint one on the other. The gauge works by measuring the resistance across each wire. As a crack develops in the specimen the wires break creating an infinite resistance. The time of each break is recorded and used to calculate the rate of travel of the crack.

Each test beam had a 10mm deep notch applied on its bottom face to act as a stress concentrator to promote crack propagation (ie the crack travels from the bottom of the specimen upwards). Note that only the beams used for measurement of crack propagation rate were notched, not those used for the standard fatigue tests. The presence of the notch was particularly important for the four-point bending test geometry since the force is distributed across the inner 90mm of the specimen and in practice cracking tends to occur anywhere over this region.

Figure 2.9 Crack propagation gauge (left); example of a gauge mounted on the side of a test beam (right)





2.3 Preparation of fatigue test specimens – field

Seal samples were obtained from SH1 site near Otaki in the North Island (RP locations were 01N-0995/ 9.560 (between 9.530 and 9.583km), northbound outer lane). The site is shown in figure 2.10, flushing was evident in the wheel paths. The slabs for the preparation of fatigue test beams were taken from between the wheel paths at 5–10m intervals, where the seal condition was good.

Four slabs of approximately 500mm long, 300mm wide and 100mm thick were cut and removed from the site (figures 2.10 and 2.11). Five beams were cut from each slab as described in section 2.1.

Figure 2.10 SH1 Otaki site showing position of slab 1 taken for preparation of fatigue test specimens

Figure 2.11 An example of a slab cut and removed from the SH1 site (left); in this case the slab partially delaminated leaving behind part of the first coat seal and was not used.

Based on the Road Assessment and Maintenance Management (RAMM) Database, the field samples consisted of four seal layers constructed between 1993 and 2010 as shown in table 2.2. The site was chosen mainly because of the available thickness of the chipseal multilayer. The test beams needed to be at least 45mm thick in order to be used in the fatigue test which is designed for asphalt beams.

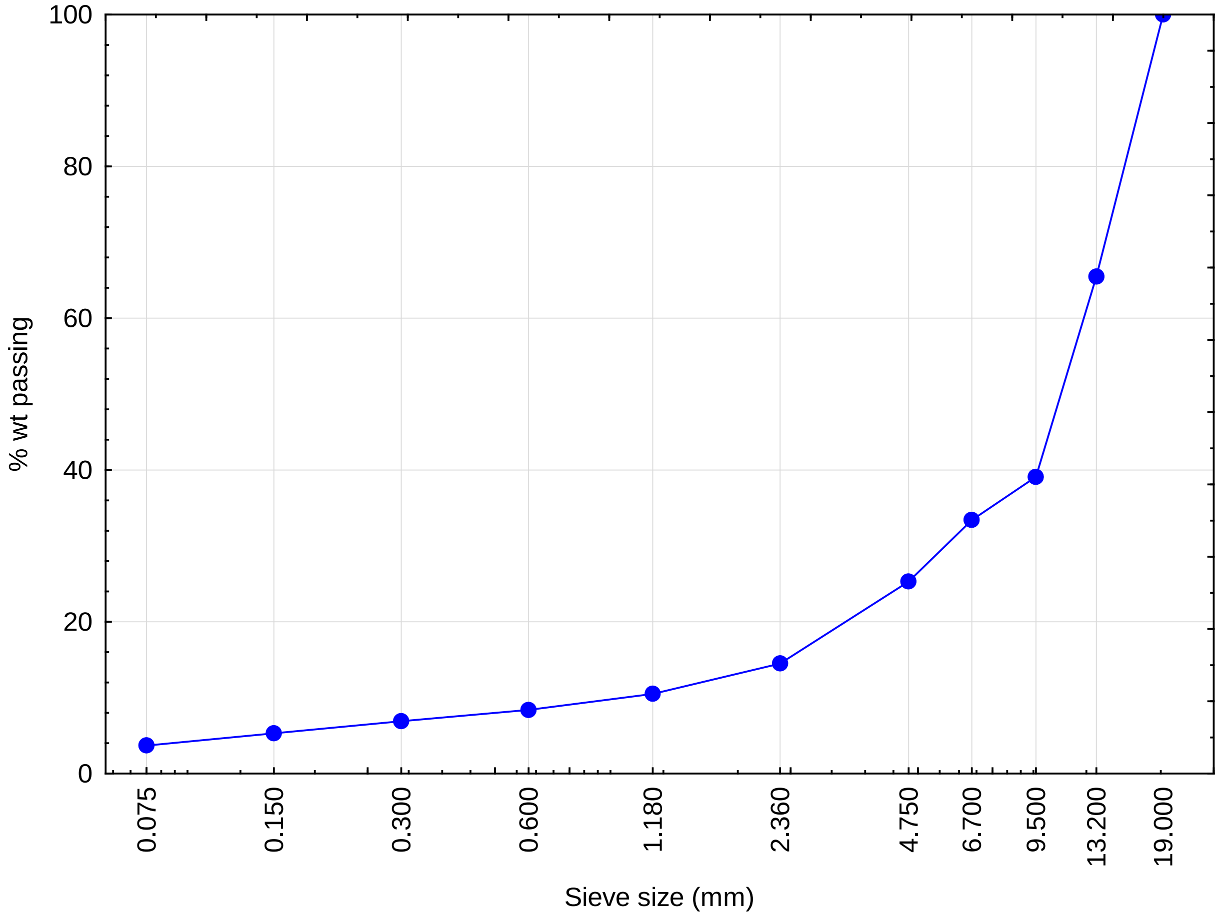
The bitumen content of the seal layer was 7.6wt% (all fines were removed using an automatic extraction system with a final centrifuge step (controls model B5). The grading of aggregate recovered after removal of the bitumen is shown in figure 2.12. A large proportion of fines breakdown material is present, typical of seal gradings (Herrington et al 2015).

Table 2.2 Seal layer information from the RAMM Database for the field samples taken for beam fatigue testing

	Seal design	1st chip size ALD[(a)] (mm)	2nd chip size ALD (mm)	Bitumen grade	Kerosene content (pph)
Top seal	Grade 2/4 two coat	11	6.7	130/150	2
	Grade 2/4 two coat	11	6.7	130/150	1
	Grade 2 single coat	11	-	180/200	3
	Grade 5 texturising seal	4.7	-	180/200	8
First coat seal	Grade 4 single coat	6.7	-	180/200	3

[(a)]ALD = average least dimension

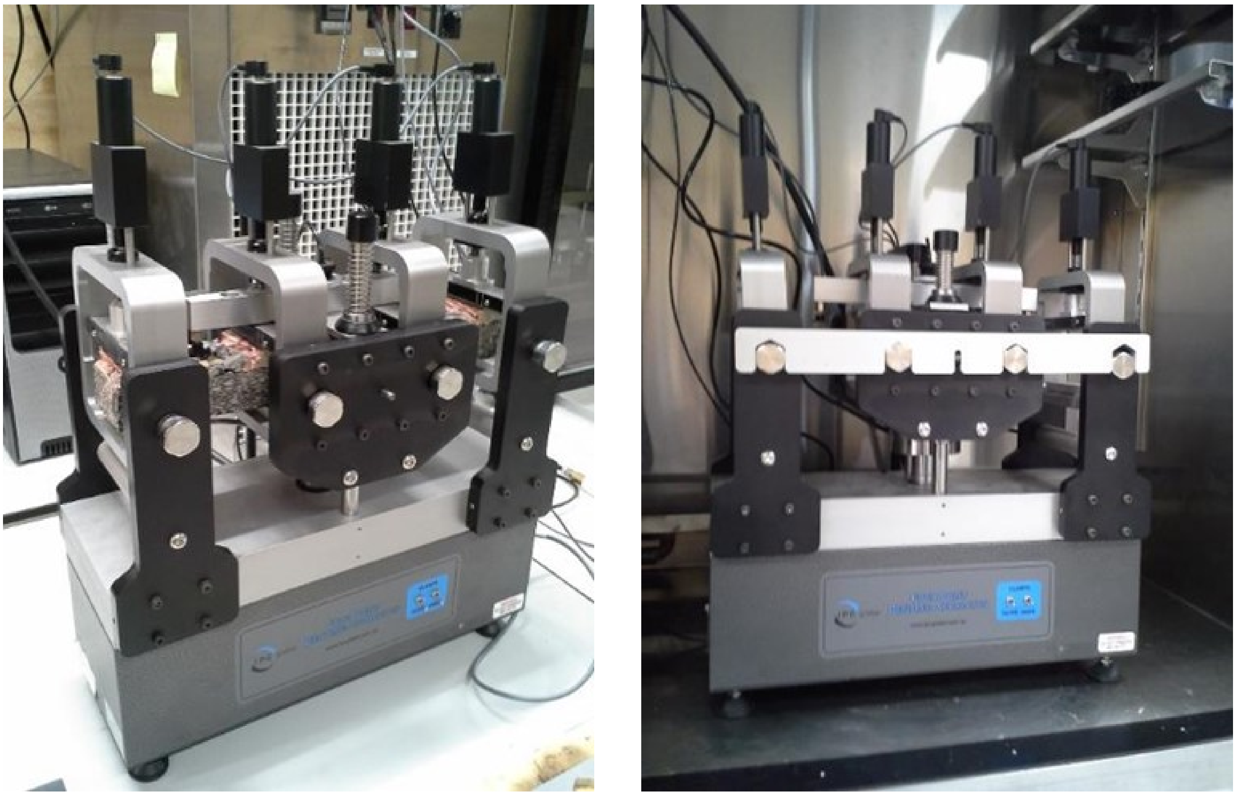
Figure 2.12 Aggregate grading for the chipseal field sample



2.3.1 Four-point bending beam fatigue test

Fatigue testing of chipseal beams was conducted according to AG:PT/T233-2006, using a specialised four-point beam bending apparatus (see figure 2.13) to determine the fatigue lives at different strain levels in the seal layers. The initial modulus value was determined from the average of the first 50 haversine loading cycles at each strain level. The loading frequency was 10Hz with no rest periods. The final test conditions adopted were 5ºC and strain levels of 200–800 με. In most cases three to four replicate specimens were tested at each strain level. For the reasons discussed below the topmost, textured seal layer was cut off to give a beam cut on all four sides.

Figure 2.13 IPC Global's four- point bending apparatus with beam mounted (left). The load is applied downwards from the neutral position so the bottom surface is in tension



3 Fatigue test results

3.1 Preliminary fatigue test experiments

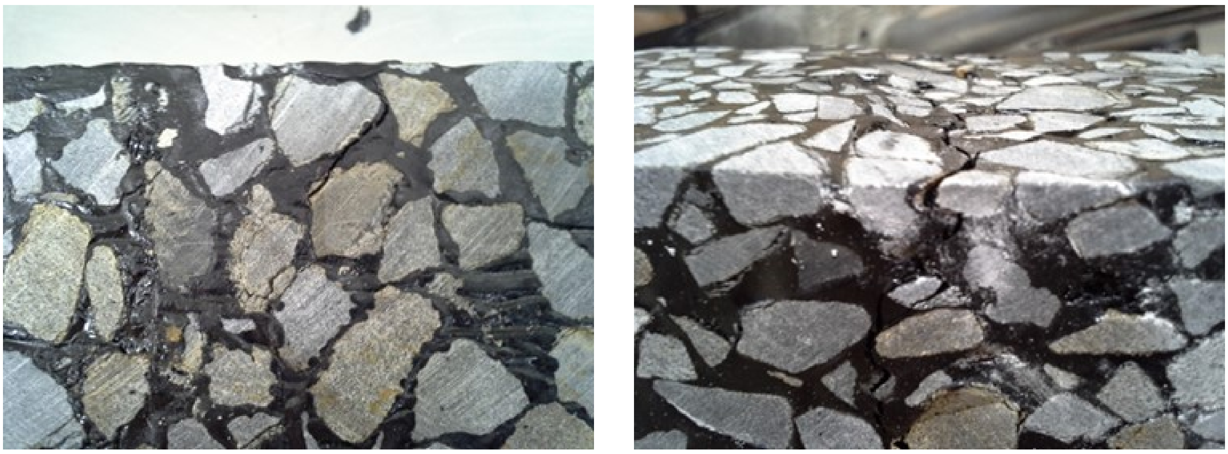
3.1.1 Optimising test conditions

Initially attempts were made to test the chipseal beams while retaining the textured surface (figure 3.1). Strips of modelling clay were applied to the surface and cured at room temperature to provide flat rigid seats for the loading clamps and the central linear variable displacement transducer. Beams tested using this system at 400με demonstrated the same fatigue behaviour as that seen in asphalts. Cracks tended to propagate around the stone surfaces (figure 3.2). However, it was found that under high deflection settings, the clay seats were prone to delamination from the seal surface during repeated loading, which led to large variations in flexural stiffness readings and thus invalid fatigue results. As a result it was decided to test beams only with cut-stone faces to improve consistency. The top 10mm of the seal beam was cut resulting in beam dimensions of 55mm high, 60mm wide and 400mm.

Preliminary tests were conducted at 10ºC but at that temperature the central section of the beam deformed and flowed noticeably under its own weight within the first few hours of testing. For that reason subsequent tests were carried out at 5ºC which resulted in no significant deformation of the beam during the period of the test.

Figure 3.1 A test beam of multi- layered chipseal with clay seatings

Figure 3.2 Photos illustrating cracks propagation as a result of repeated loading



3.1.2 Rate of crack propagation

An attempt was made to directly measure the rate of crack propagation through the seal beams using the fatigue test set up with the attachment of a crack gauge. Unfortunately mounting the gauge was found to be very time consuming and the experimental set up was prone to producing invalid outcomes. The main difficulty was the inability to ensure the crack propagated where the gauge was located. Although the crack formed at the top of the notch, the subsequent path was unpredictable due to the variation in orientation of the aggregates, combination of layers and grading. Thus frequently the crack would propagate sideways outside the relatively small area (20mm x 20mm) covered by the gauge. A larger crack gauge would help resolve the issue, but this specialised (single use), gauge was extremely expensive and impractical to source from overseas within the timeframe of the project. An optical system to measure crack growth may be cheaper and more efficient.

For the one (partially) successful experiment, the beam sample was tested using a tensile με of 800 (equivalent to an average vertical deflection of 0.45mm) at 5ºC, and a testing frequency of 10Hz. Figure 3.3 shows the beam after testing, the change in flexural modulus and progression of the crack with respect to time (number of cycles) is shown in figure 3.4.

The exponentially decreasing flexural modulus is the same behaviour as that typically observed when testing asphalt beams. Data for the first 5mm of crack growth could not be recorded due to problems with the gauge connections. Over the range recorded the crack growth rate was linear (2.7mm per 10,000 cycles). The early growth rate would probably have followed the exponentially increasing rate usually observed in the testing of metals and polymers (Roesler et al 2007), marked by the dotted line in figure 3.4

An important observation is that over the range of loading cycles spanning the measured crack growth rate data, the decrease in flexural modulus is also approximately linear, ie the rate of crack growth is directly proportional to the decrease in beam strength (figure 3.5). This indicates that under the test conditions used the decrease in modulus was due to the crack formation, not to some other effect related to flow or deformation of the bitumen and the test results could be interpreted directly in terms of fatigue cracking.

The work demonstrated that direct measurement of crack growth rate is feasible and the method may be potentially useful as a means of relating layer strain in the field (derived from falling weight deflectometer data), to crack growth rate, but due to time and budget constraints it was not possible to pursue this concept further within the project.

Figure 3.3 Crack gauge after a successful data acquisition

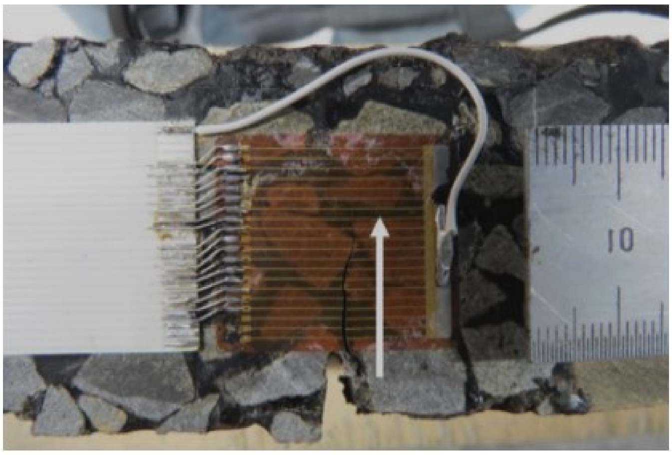


Figure 3.4 Measurement of crack growth during fatigue testing

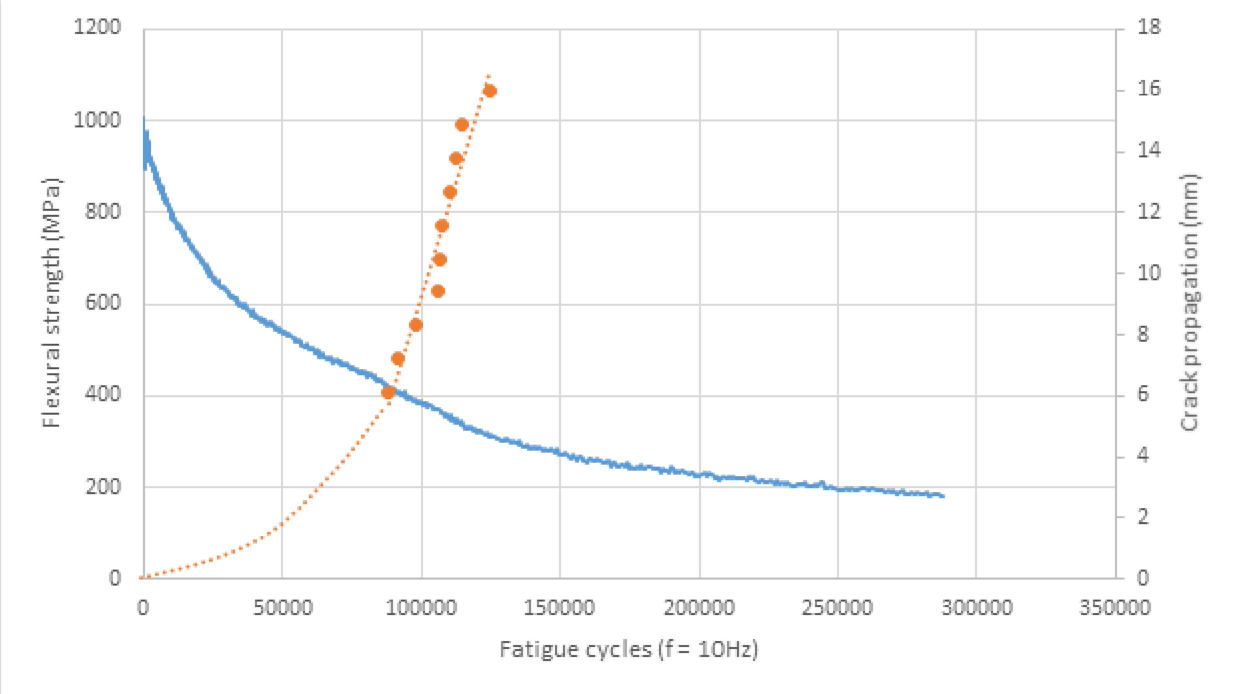
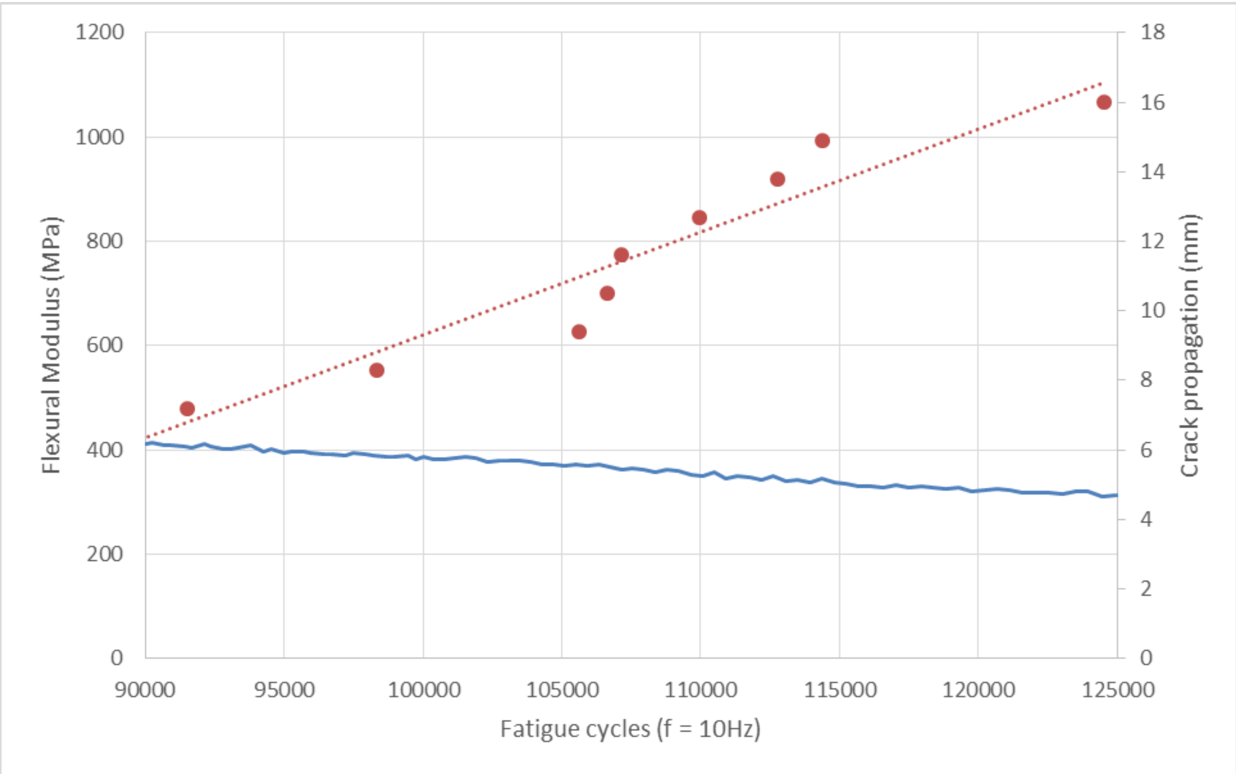


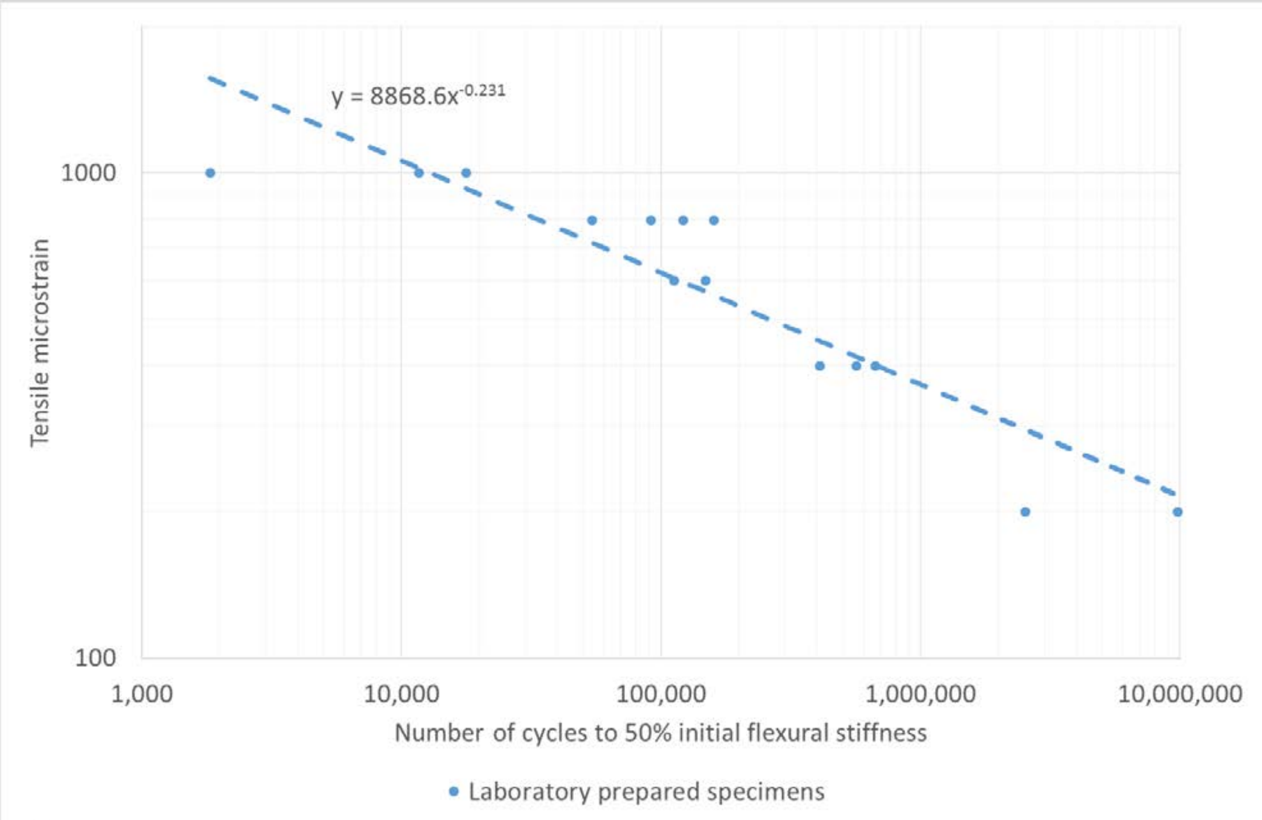
Figure 3.5 Crack growth rate data showing approximately linear change in flexural modulus



3.2 Fatigue test results for laboratory-prepared samples

Results of fatigue tests carried out at 5ºC on chipseal beams manufactured in the laboratory are shown in figure 3.6. As expected the fatigue life decreases with increasing strain level. The initial flexural moduli data shows considerable scatter (1200±200 MPa (95% CI)) but no statistically significant trend (95% confidence level), with strain level, indicating that the beams were behaving elastically (at least at the 10Hz testing frequency used). Tests done at 100µε proved there was an endurance limit where the fatigue life of the chipseal became effectively infinite. The tests showed little reduction in the initial flexural modulus over 5,000,000 cycles (~6 days of continuous testing) and showed no sign of reaching 50% of the initial value. This phenomenon has previously been reported for fatigue lives of hot mix asphalt samples (eg Carpenter 2003; Prowell et al 2010). Carpenter claims that a continuous physical-chemical healing reaction occurs, even during continuous loading, at low strain levels. If damage due to loading falls below a certain level, then damage accumulation is virtually non-existent.

Figure 3.6 Fatigue test results for laboratory prepared chipseal beams



3.3 Fatigue test results for field samples

Fatigue test results for chipseal beams cut from field samples are shown in figure 3.7 superimposed on the laboratory sample results. The fatigue lives obtained are lower than those of the laboratory specimens. At 800µε the number of cycles to 50% of the initial modulus is approximately 3,000 compared with 33,000 for the laboratory specimens. This observation is consistent (by analogy with asphalt mix), with the lower bitumen content (7.6% compared with 10%), and the significantly higher initial flexural modulus of the field specimens (4,100 ±1,000 MPa compared with 1,200 ± 200). The fatigue life is known to increase exponentially with the volume of bitumen present and decrease exponentially with the specimen modulus. As with the laboratory prepared specimens the initial flexural moduli showed no statistically significant trend (95% confidence level) with strain level, indicating the beams were behaving elastically at the 10Hz testing frequency. The viscosity of bitumen extracted from the seal (with layers dating from 1993–2010), was 1,250 Pas at 50ºC and 0.005s^{-1} shear rate. This figure is much lower than that obtained through laboratory oxidation (see section 3.4), but the results are not directly comparable as the initial bitumen grades were different and the field sample binders still probably retained the heavy ends of the kerosene used in construction.

The chipseal beam fatigue data is compared with that for asphalt mix in figure 3.8 (data points have been removed for clarity). The data is for a New Zealand asphalt concrete (AC) 14 mix (60/70 bitumen), tested by Saleh (2010) at 20ºC using exactly the same test conditions at that used here (except for temperature). At 400 µε the asphalt mix has a fatigue life of 500,000 cycles.

Peploe (2008) prepared 10 mixes to the National Asphalt Specification (AAPA 2004) and TNZ M/10 (Transit New Zealand 2005) using 50/50, 60/70 and 80/100 binders. The fatigue life (50% initial modulus) of the mixes was measured at 400µε using the same test method as that used here except at 20ºC. The average fatigue life was 600,000 cycles, very close to that reported by Saleh.

Figure 3.7 Fatigue test results for chipseal field samples compared to laboratory prepared seals

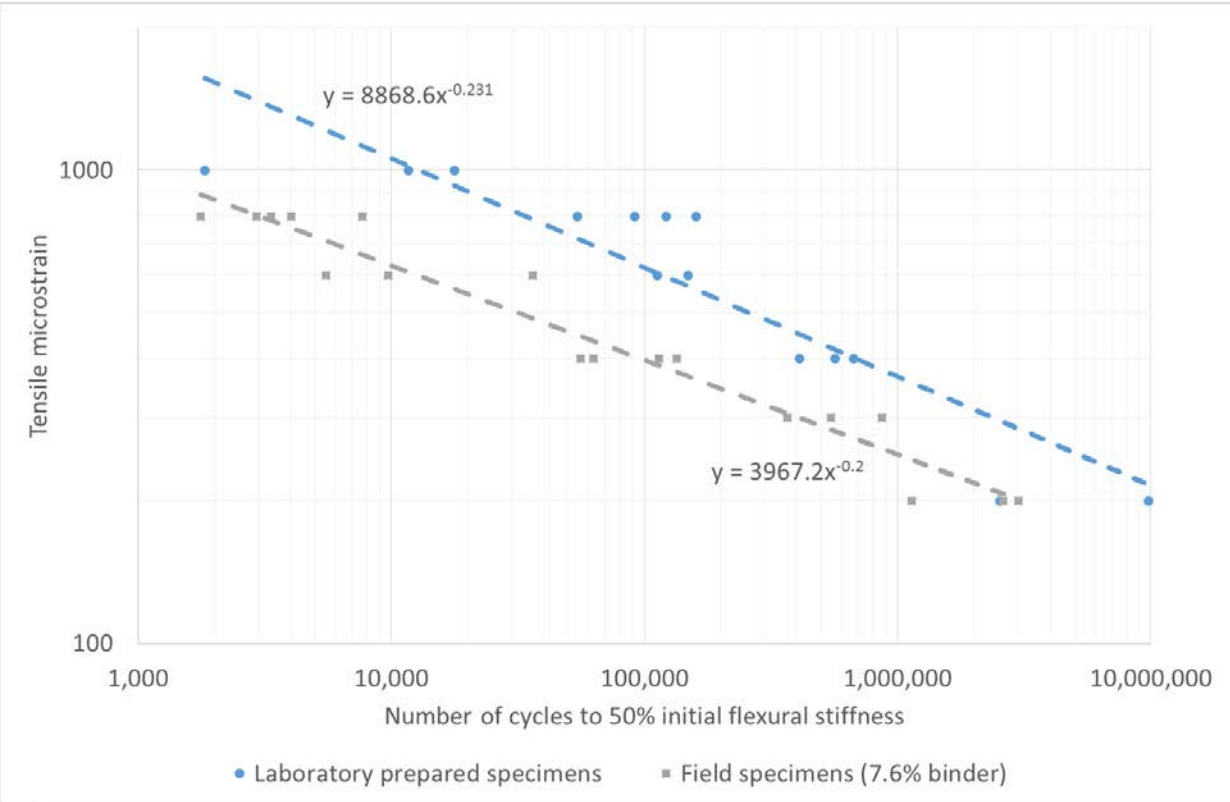
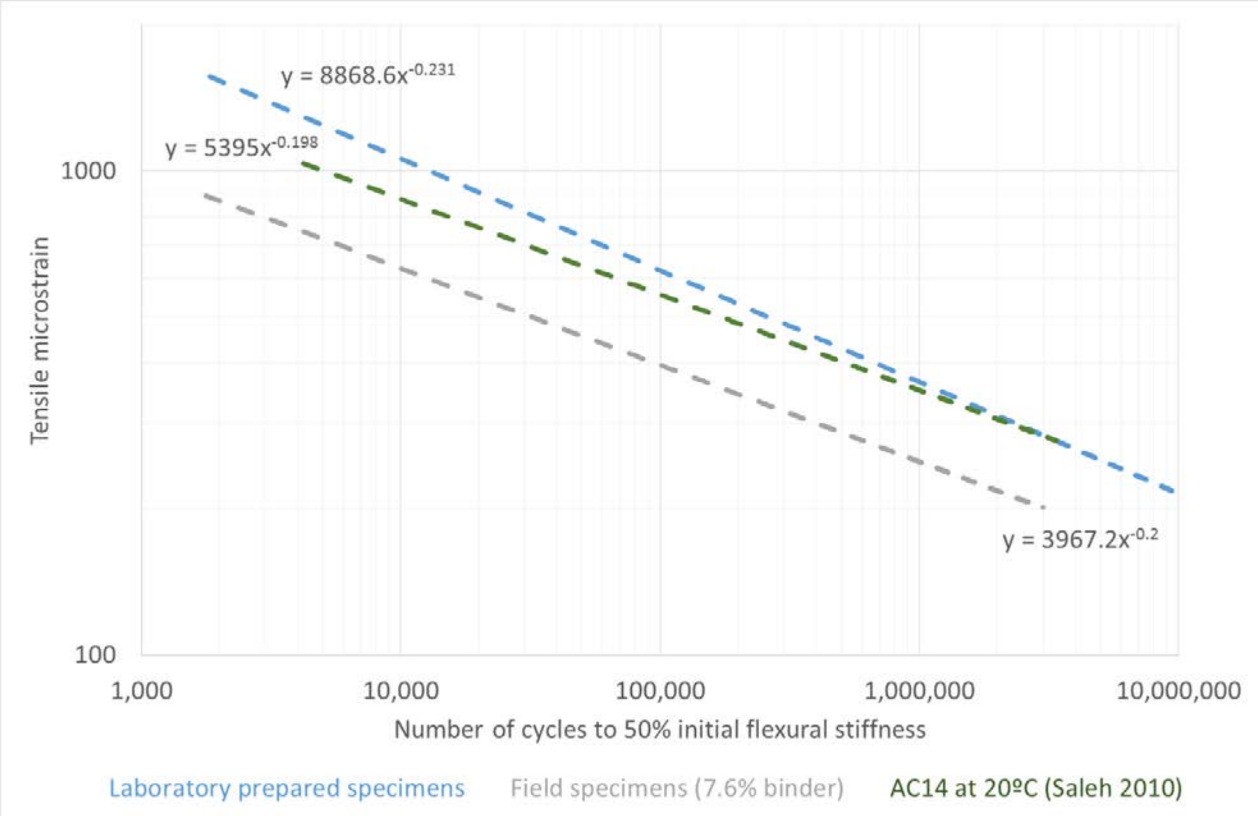
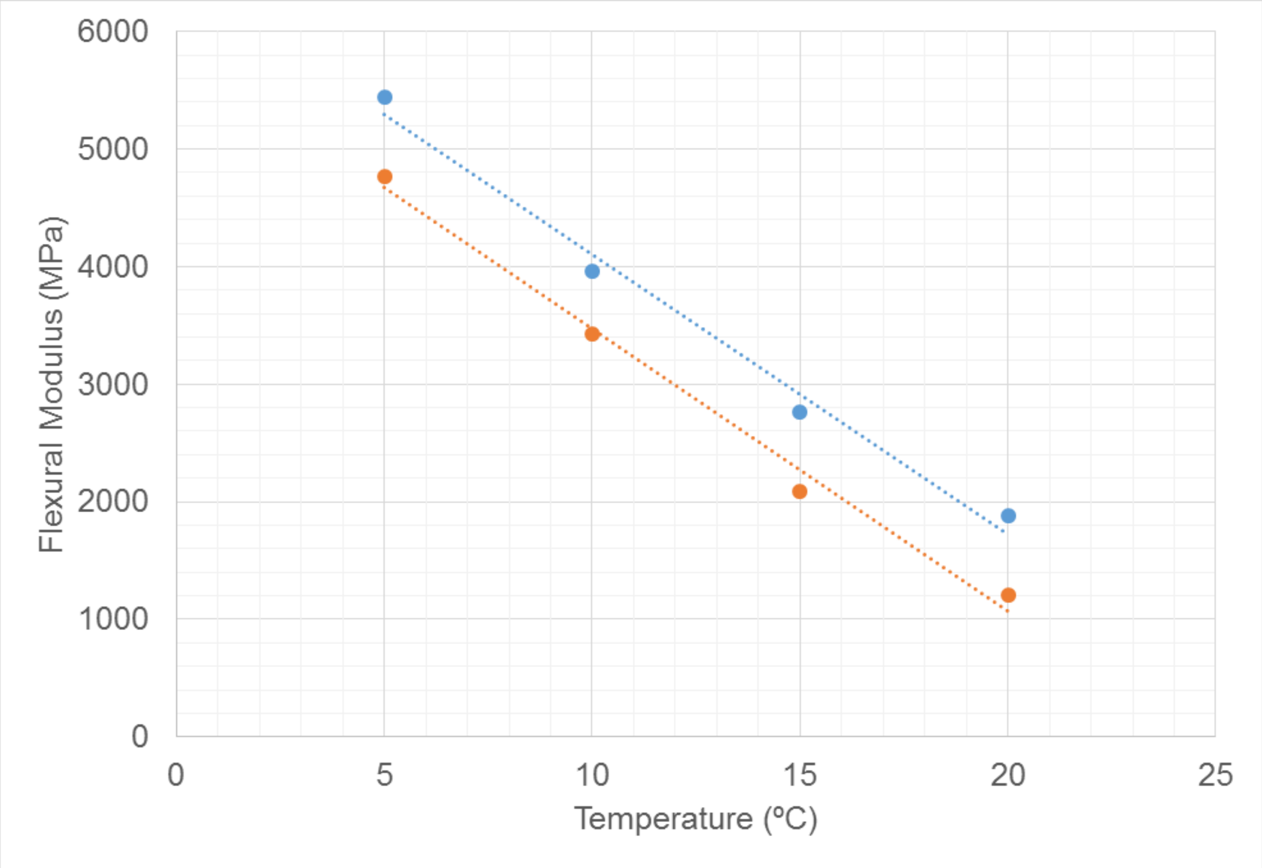


Figure 3.8 Comparison of fatigue test results for chipseal and asphalt specimens tested at 5ºC and 20ºC respectively (points omitted for clarity)



The field and laboratory chipseals tested in the present work have, at 400με, fatigue lives of 95,000 and 700,000 respectively, but measured at 5ºC (because of problems with deformation of the sample over long time periods at higher temperatures). At 20ºC the seal binder is softer and the modulus of the seal beams substantially lower which would give a much longer theoretical fatigue life. The moduli at 400με (average of the first 100 loading cycles), of two field sample beams were measured at a range of temperatures up to 20ºC (figure 3.9). The moduli decrease linearly and the average ratio of the moduli at 5ºC to that at 20ºC is 3.6. This is somewhat greater than the value found by Stubbs et al (2010) for AC14 asphalt mixes made with 60/70 grade bitumen and under the same loading conditions.

Figure 3.9 Effect of temperature on the initial flexural moduli (at 400με) of two field sample seal beams



For asphalt mixes fatigue life has been found to be related to the specimen modulus through equation 3.1 (Monismith et al 1985; Baburamani 1999):

$$N_f = \frac{a}{E^b \varepsilon^c} \quad \text{(Equation 3.1)}$$

Where, N_f = the number of load cycles to failure, *E* is the elastic modulus of the material, *ε* is the tensile strain at the bottom of the specimen and *a, b, c* are material dependent constants. This equation was used with data reported by Stubbs et al (201), to make an estimate of the fatigue life of an AC14 asphalt mix made with 60/70 penetration grade bitumen. At a constant strain level equation 3.1 reduces to equation 3.2:

$$N_f = \frac{K}{E^b} \quad \text{(Equation 3.2)}$$

Where K is a constant, and hence at 20ºC:

$$N_{f20} E_{20}^b = K \quad \text{(Equation 3.3)}$$

and for the same material at the same strain, at 5ºC:

$$N_{f5} E_5^b = K \quad \text{(Equation 3.4)}$$

Equating equations 3.3 and 3.4 and solving for N_{f5} gives equation 3.5:

$$N_{f5} = \frac{N_{f20}\, E_{20}^b}{E_5^b} \quad \text{(Equation 3.5)}$$

Various values of the exponent, b are reported in the literature, for example: 0.726 (Harvey et al 1995) and 2.363 (Ali and Tayabji 1998). For this analysis the value of 1.8 taken from the Shell model (Shell 1978), and adopted by Austroads (2008), was used.

From Stubbs et al (2010) the AC14 mix modulus at 20ºC, E_{20} = 4250 MPa and E_5 = 11600 MPa. Using a value of N_{f20} = 550,000 cycles the predicted value of N_{f5} is about 90,000 cycles. This value is comparable to the measured fatigue life of the chipseal field samples and almost eight times less than that of the laboratory seal specimens.

Additionally asphalt fatigue lives can increase by factors of about 2 to 10 times if rest periods are used in the test method to allow healing of micro-cracks (Baburamani 1999). The same effect should also be observed in chipseal specimens and is likely to be relatively greater for the seal specimens because of the greater film thicknesses present.

The results above need to be confirmed with more extensive testing, but these preliminary findings indicate that in the field the higher bitumen volumes and lower moduli of multiple layer chipseals would result in fatigue lives equivalent to, and possibly well in excess of those expected from asphalt mixes under the same temperature and loading conditions. This conclusion, however, seems inconsistent with the observation that significant amounts of cracking appear to develop in chipseals very early in their life. Towler et al (2010) report that in the 2008/09 season about 14% of total resealing length for seals that failed prior to the RAMM expected life was due to cracking. However, only 8% of resealing of seals up to twice the expected life, was for cracking.

A possible explanation is that cracking is occurring in seals not through ‘normal’ fatigue processes but due to very large strains caused by severe but localised failure of the pavement structure. This may be a small basecourse area poorly compacted during construction but more probably arises from water damage to the basecourse and, as discussed below, the seal layer.

3.4 Effects of bitumen oxidation on fatigue life

In order to simulate in-field ageing, the bitumen used to manufacture the seal test beams was deliberately oxidised by aeration at a high temperature. The final viscosity of the aged binder was about 10,790 Pas at 50ºC and a shear rate of 0.005s^{-1}. This is significantly higher than the original bitumen viscosity of 890 Pas (0.005s^{-1}). Data derived from infrared spectroscopic analysis of bitumen samples exposed outdoors in Lower Hutt for 16 years, was used to estimate an approximate equivalent field age (and based on the *increase* in viscosity at 50ºC), for the bitumen (figure 3.9).

The estimated field age was about four to five years (in the Lower Hutt climate). This represents a significant increase in bitumen viscosity. Most oxidative hardening of bitumen in the New Zealand chip occurs within the first three years, after which the rate of hardening is much slower (see below).

Fatigue test results for chipseal beams made with the oxidised bitumen are compared to those of the original bitumen, the field samples and asphalt in figure 3.10. Oxidation of the bitumen had no significant effect on the seal beam moduli (at 5ºC). Interestingly, however, the results suggest that oxidation had a small (with respect to the precision of the measurement), but positive effect on fatigue life. At 800με the mean initial flexural moduli and cycles to failure were 1,200 ± 200MPa and 33,000, and 1,300 ± 400MPa and 84,000 respectively. An increase in fatigue life for oxidised bitumens (ie not mixed with aggregate) has previously been reported by (Hintz et al 2011*).*

Generally the fatigue life of asphalt mixes will decrease as the binder hardens (and the initial modulus increases), but the results presented here suggest that much greater than four to five years in the field would be needed to achieve such an effect in seals.

Researchers at ARRB Group investigated the binder viscosity at which seal 'distress' first occurs in seals in Australia (the work is summarised by Choi et al 2014). Distress included both cracking and chip loss. A value of approximately 470,000 Pas (5.67 log Pas at $0.005s^{-1}$ shear rate and 45ºC) was identified. In the New Zealand climate an 80/100 bitumen in a chipseal, initially with a viscosity of 2,500 Pas at 45ºC and $0.005s^{-1}$ shear rate, increases to between about 10,000–30,000 Pas after eight to nine years, most of this increase occurring in the first three years (Ball 1999). Under New Zealand conditions bitumens in chipseals are unlikely ever to reach the critical distress value found in Australia. It has been claimed that the reason for this is that flushing of the sites from which the data was gathered led to 'softer' bitumen from underlying layers mixing with oxidised material from the top seal (Oliver 2003). Similar behaviour though was reported by Ball for artificial seals without underlying seals exposed outdoors and is consistent with the known effects of temperature on bitumen oxidation rate (Herrington 2000), so is also probably strongly related to climate. In any case New Zealand seal binders do not reach the critical viscosity found in Australia, which is consistent with the very long fatigue lives proposed here on the basis of comparison with asphalt mixes (see section 3.2), and provides further support to the idea that fatigue cracking only occurs in New Zealand seals because of localised very high defections.

Figure 3.9 Equivalent (Lower Hutt) field age for laboratory oxidised bitumens based on the viscosity at 50ºC

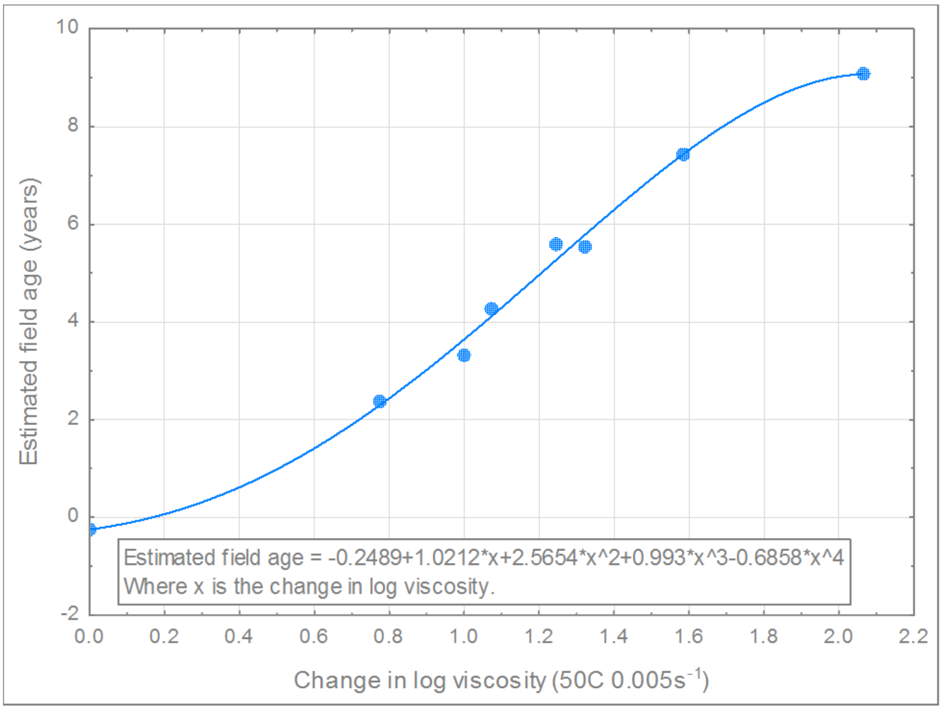
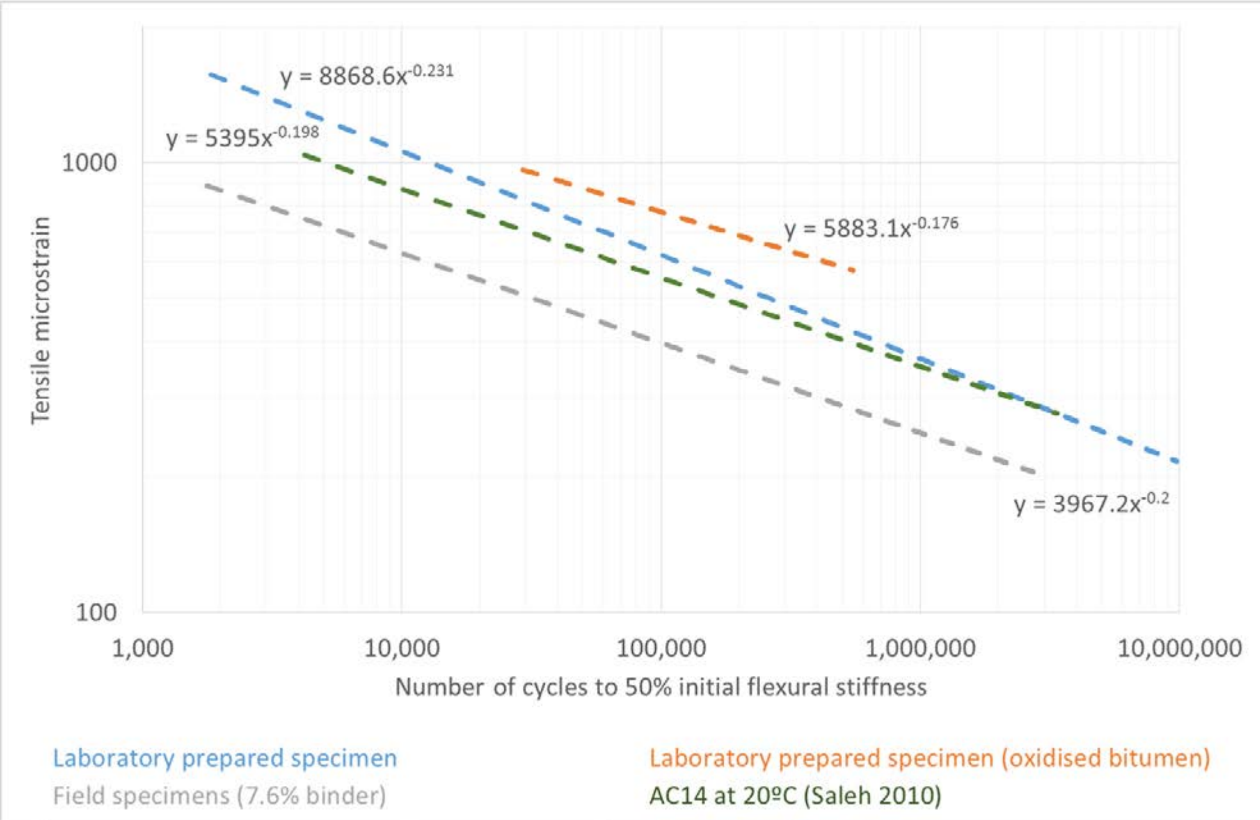


Figure 3.10 Fatigue test results for laboratory prepared beams using oxidised bitumen



3.5 Relationship between chipseal cracking and flushing

The fatigue test results obtained above indicate that fatigue cracking occurs in chipseals through unusually large deformations in localised areas. This may be brought about through water ingress and weakening of the basecourse but recent work also suggests that water damage to the bottom layers of multi-layer seals could also be a significant contributing factor.

Flushing and cracking are often observed together (figure 2.2). Recent investigations into seal flushing have found that in multi-layer seals binder can be stripped from the bottom of the layer by water and forced to the top of the layer (Herrington et al 2015). This 'sub-surface stripping' leaves a weak layer of unbound chip that may gradually compact or 'collapse' under traffic to produce a rut and result in large deflections.

This mechanism requires that water is held at the base of the seal layer and only drains through the pavement very slowly. The process may be initiated by water entering through a seal defect that then leads to sub-surface stripping (and pavement damage) resulting in increased deflections and cracking. Alternatively a poorly compacted area of basecourse may result in high deflections and cracking, which then allows ingress of water that causes stripping.

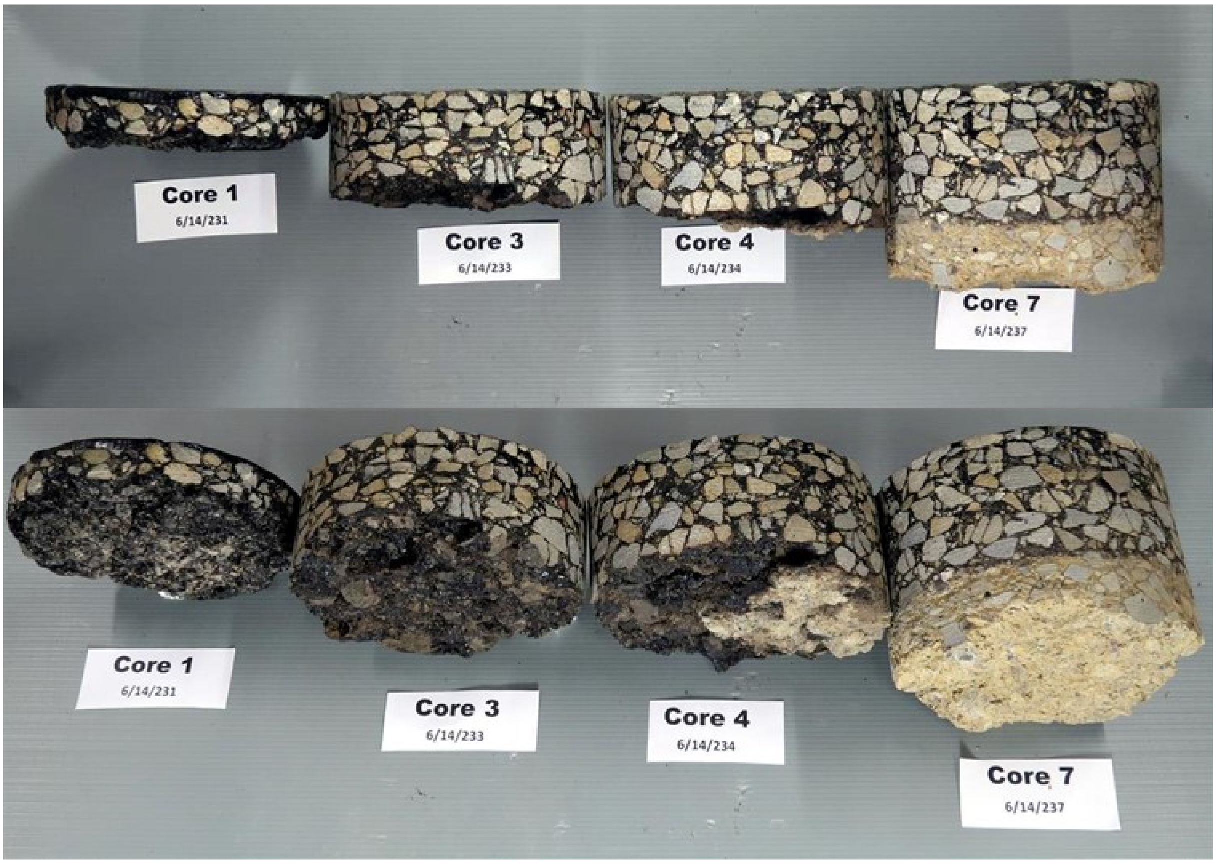
This phenomenon appears relatively common. An example is shown in figures 3.11 to 3.13 (Herrington et al 2015). This site (SH 57 near Shannon) showed a flushed patch with alligator cracking (core positions 1 and 2 in figure 3.10), but no cracking was present on the adjacent seal (core positions 3 to 7). The seal structure (ie the sequence of seals that had been applied) was the same at all core positions. Opening one of the cracks showed the seal inside the crack had been stripped of bitumen (figure 3.11). The seal beneath the surface had also been stripped and was loose in the core hole (figure 3.12). The extent of the stripping decreased from core 1 to 7. It appears that stripping of the seal base allowed a significant increase in the deflection, producing cracks that were then scoured by water.

Whether water first gains entry in these cases through a crack developing from defections caused by localised poorly compacted basecourse, or some other defect such as chip loss or roll-over cannot be determined without further investigation. On the whole given the prevalence of water-induced flushing damage observed on the network and recent work on the permeability of newly constructed seals (Alabaster et al 2015), the latter seems more likely.

Figure 3.11 Cracked and flushed seal site (SH57 Shannon) showing core sample positions

Figure 3.12 Cracked seal surface (left) and interior view of a crack showing the stripped seal (right)

Figure 3.13 Progressive development of sub- surface stripping, core 1 (cracked seal), other cores from un-cracked seal



4 Chipseal crack repair

The following discussion covers international and New Zealand practice for crack repair. Crack repair in the present context refers to the repair of specific, individual cracks rather than dig-outs, resealing or applying a large patch of asphalt or seal that overlays both the cracks and areas of intact surfacing alike.

A draft practice guide has been prepared and is presented in appendix A.

4.1 Crack repair systems

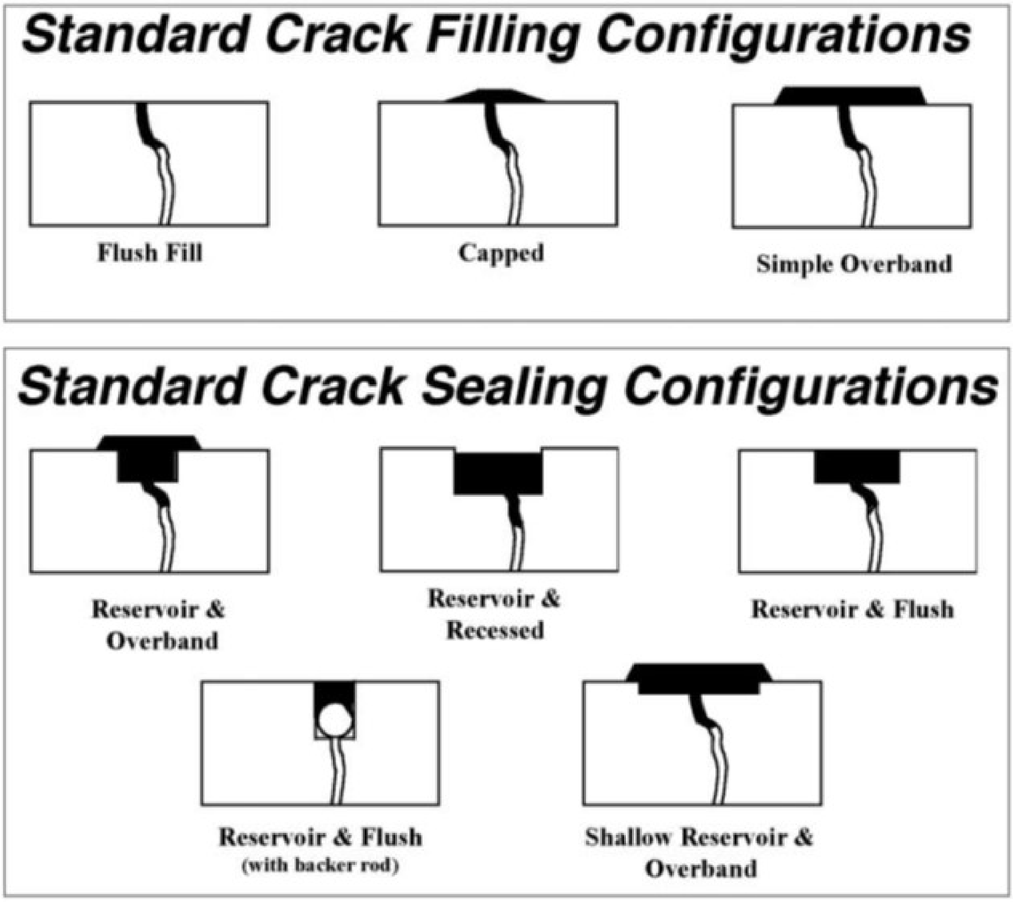
Crack repair services are offered by a number of contractors in New Zealand. Typically a polymer-modified binder is applied hot from a hand wand. Other non-bituminous polymeric materials are also available as sealants. Some sealants may be fibre modified. Cold applied emulsions (bitumen or polymer-modified bitumen emulsions) can also be used. They are cheaper and fill narrow cracks easily but research in the USA suggests that hot applied sealants have substantially longer lives (at least for cracking in asphalts). Research in the USA also indicates that crack sealing of asphalt can increase the life of the surfacing by more than six years but is highly dependent on how well the crack is prepared beforehand. There is apparently no published data available on the performance of different materials in New Zealand conditions or the overall effectiveness of crack sealing.

The crack should first be cleaned of debris (which can be accomplished with an air gun) and be dry to ensure a good bond to the sealant (obviously this is less important for emulsion systems). Several approaches can be taken to crack repair as illustrated in figure 4.1.

The most common methods used in New Zealand are variants of the flush fill and capped or over-banding (bandaging) approaches. These methods are simple and cheap but the edges of the bandage may be susceptible to being peeled off by traffic. Bandages are usually applied as liquids but tapes and preformed strips, heat sealed to the road, can also be used. The extent of crack filling as opposed to simple crack bridging will depend on the crack width and viscosity of the sealant. In some cases if the crack is very wide then a packer or filler material (eg sand or fine asphalt) of some sort is required to fill the crack to near the surface to prevent the sealant draining away. Skid resistance and pick-up onto tyres of sealant may be a problem in some cases but can generally be avoided by sanding (blotting) or adding a fine chip to the surface.

The reservoir methods (also known as inlaid systems or rout and fill) require the crack to be widened at the top with a router, typically to 20–40mm wide and 15–20mm deep. This is seldom if ever done in New Zealand. The approach is based on the belief that wide shallow bands of sealant (typically with a width to depth ratio of 2–4 to 1) above the crack perform better by reducing the strains in the sealant by thermal expansion and contraction. This is unlikely to be a problem in New Zealand where minimum winter temperatures are generally much higher than in the USA or Europe; however, the same reasoning would also apply to strains induced by differential movement of the crack faces. The routed faces also provide good adhesion for the sealant which is also recessed and protected somewhat from traffic.

Figure 4.1 Crack repair methods; summary of US practice for asphalt surfacings



Source: Masson (2003)

4.2 Crack repair of chipseals

In theory repair of cracking in seals at an early stage of development should help extend the life of the surfacing by protecting the pavement from water ingress. Large cracks also need to be repaired before resealing. If cracking has advanced to the stage where basecourse fines are 'pumping' through to the surface and blocks of the surfacing are moving under traffic then crack repair is unlikely to be successful and will have a very short life. Other forms of repair (dig-outs, patching) are needed in that case.

If cracking is less advanced then a variety of crack sealing materials and systems are available as discussed above. Typically these products have been developed for use on asphalt surfacings and are usually hot-applied polymer-modified bitumen, but polymer-modified bitumen emulsions are also sometimes used.

Where cracks are about 1 to 10mm wide the over-band approach can be used to create a 'bandage' 2–3mm thick and up to 100mm wide. This is the most commonly used approach in New Zealand.

On 5–15mm wide cracks, routing of chipseal surfaces is possible but more difficult than with asphalts as damage of the surrounding seal through chip loss surrounding the crack is likely. The literature indicates that routing of seals (as opposed to asphalts) for crack sealing is carried out in the USA but how common the practice is, is unclear.

In general the crack sealing of chipseal surfacings, as a routine maintenance tool is relatively limited in New Zealand. Possible reasons for this are:

- Cracking in seals is often less obvious and the cracks themselves have less well-defined edges than in asphalts, making it difficult to achieve complete coverage and a water-tight join of the repair material to the seal.
- Cracking in chipseals is predominantly alligator cracking so the length of cracking in a relatively small area can be very large. As the cost of crack sealing is approximately $5 to $7 (and above) per linear metre, this is likely to make individual crack sealing uneconomic for seals with large amounts of cracking (in comparison chipseals typically cost in the order of $5 to $7.50m^{-2}).
- Cracking in chipseals is often associated with flushing. Severe flushing results in the sealant bandage adhering to a soft bitumen mastic which will reduce the life of the repair. This type of failure would generally require pavement repair rather than bandage crack sealing.

4.3 Specifications

There is apparently no NZ Transport Agency (the Transport Agency) or other national specification covering materials and practices for crack sealing of chipseal or asphalt surfacings in any detail.

The specification TNZ C6:1995 (*Repair of surface defects*) (Transit NZ 2005) specifies use of bitumen for filling cracks up to 5mm wide, a bitumen aggregate (slurry) for cracks 5–20mm and a fine asphalt mix for wider cracks. In those cases a waterproof seal coat is specified following crack sealing. Proprietary polymer-modified materials are allowed with no requirement for immediate resealing, but no performance or material properties are specified.

Numerous overseas specifications for sealant materials are available, many of these are developed by US states for local use. The most widely used specification in the USA is ASTM D 6690-12 (*Joint and crack sealants, hot applied, for concrete and asphalt pavements*) (ASTM 2012). Sealants are specified as types I to IV based on their tensile extension at -29ºC. Other properties measured include cone penetration at 25ºC and resistance to water dis-bonding. A criticism of the specification is that it does not deal with ageing (oxidation) of the sealant which is likely in practice. The specification is reported as not correlating well with field performance.

A performance-based specification has recently been postulated in which the bending beam rheometer and dynamic shear rheometer are used to measure properties more closely related to field performance but has not been widely adopted as yet.

The emphasis in the US specifications is on low temperature properties, essentially flexibility and resistance to thermal cracking and delamination. The low temperatures experienced in continental winters (to -30ºC or below) are well in excess of those found in New Zealand.

In the UK, crack sealing materials are assessed and certified under the Highway Authorities Product Approval Scheme (HAPAS). This includes a range of performance and material tests but the conditions and nature of some of the tests performed depend on the specific characteristics of the particular material being assessed (for example the manufacturers recommended application temperature). Key properties specified include resilience (elastic recovery), skid resistance, wheel tracking rutting rate (for inlaid or reservoir systems) and elongation (ductility).

4.3.1 Concepts for a New Zealand specification

International specifications relating to road crack sealing largely focus on controlling the properties of the sealant materials. A drawback with this approach is that the success of crack sealing repairs also depends very strongly on the preparation of the surface and the method used and skill of the operator in application of the sealant.

A better approach to developing a New Zealand specification would be to follow that adopted for high friction surfacings (pilot specification P25), another specialist maintenance treatment, in which a minimum performance level is set for the duration of a defects liability period. In some US states (eg Michigan) a warranty period of two years is used. This period is for crack sealing of asphalt surfacings and its suitability for repair of chipseals would need to be investigated.

Satisfactory performance would be assessed in terms of:

- the absence of significant tracking or bleeding
- the absence of potholes on a repaired crack
- the percentage of repaired crack length that had failed, defined as:
  - reopening, spalling or widening of repaired cracks
  - loss of adhesion of the sealant bandage to the surface.

In addition some basic physical test requirements would be set to exclude obviously unsuitable materials. These would be based on overseas specifications (which many proprietary sealant materials used in New Zealand would already meet). Key properties are suggested in table 4.1.

Table 4.1 Proposed test properties for inclusion in a New Zealand specification

Property	Test	Method	Purpose
Consistency at road temperature after accelerated ageing	Cone penetration at 25^{0}C before and after heating at 70^{0}C for 28 days	EN 13880-2	% retained penetration to control increase in stiffness of the material as it oxidises and to ensure maintenance of bond to the surface
Consistency at high road temperatures	Flow resistance at 60^{0}C	EN 13880-5	Resistance to bleeding and pick-up
Elasticity after accelerated ageing	Resilience 25^{0}C before and after heating at 70^{0}C for 28 days (alternatively the torsional recovery test as used for polymer modified binders.	EN 13880-2	Elasticity and retained elasticity after oxidation and to maintain resistance to crack movement.
Friction	British pendulum tester	UK HAPAS guidelines	Ensuring adequate skid resistance

5 Chipseal crack progression

5.1 Introduction

Understanding the rate of crack progression and its effects on the pavement is necessary in order to evaluate the potential effects of delaying maintenance. In order to define crack progression we used data collected over the past 13 years on the 145 Transport Agency long-term pavement performance (LTPP) sites. The LTPP programme is designed to provide sufficient detailed pavement condition data to facilitate detailed pavement deterioration analysis. Data is collected at each site on an annual basis, and includes a visual inspection which identifies and records all pavement distress including cracking information.

The cracking data was extracted from the visual condition data files for each site and then analysed to determine crack progression and crack growth. Both the rate at which an individual crack grows and the rate of crack growth in a specified area in terms of increased area as multiple cracks develop was determined. Furthermore climatic conditions, traffic volume and drainage at each site were analysed to determine which of these factors influenced crack growth.

As the data from the LTPP sites is collected annually, a separate site inspection programme was undertaken to determine whether changes over a shorter inspection period revealed any additional information. Four state highway sites were selected and the cracking observed was recorded with the aim of identify or quantifying changes that might occur over a shorter period.

5.2 Methodology

The research plan to quantify crack progression was divided into the following components:

1. Retrieval of crack data from LTPP site data
2. Evaluation of condition data – elimination of sites
3. Determination of individual crack growth
4. Determination of total cracked area and rate of progression
5. Identification of factors that affect crack growth
6. Detailed site inspections.

The following sections summarise the individual components of the research plan and provide details of the steps taken to achieve the results.

5.2.1 Retrieval of crack data

Pavement condition data collected annually as part of New Zealand's LTPP programme provided the bulk of the crack data used to define crack progression. Pavement condition data is recorded annually through a detailed visual inspection and manual measurements at each of the 145 LTPP calibration sections on New Zealand's state highway and local authority roads. Each site is subdivided into 12 50m subsections (six in the increasing lane and six in the decreasing lane. The location of the distress (crack type) is defined by measuring the distance from the subsection start. Transverse cracks have a start location and a width measurement while longitudinal cracks have both a start and end measurement. Where multiple cracks are present a start and end location and/or width measurement may also be recorded for transverse and longitudinal cracks respectively. Cracks are divided into narrow (<3mm) and wide (>3mm) but for the purposes of this research there was no distinction between narrow and wide cracks. This information along with the crack type and a comments field was recorded in an Excel spreadsheet, a typical spreadsheet is depicted below in table 5.1. The same data collection process formulated in year one was replicated for each of the 13 years of the project, producing data in sufficient detail to follow the growth of both individual cracks and the total cracked area within a calibration site.

Table 5.1 Cal23 condition data

Date	Sub sect	Dist start	Dist end	Dist width	Distress	Comments
18-Nov-13	1	0	50	3,000	f2	lane
18-Nov-13	2	0	50	2,900	f2	lane
18-Nov-13	2	37	39	100	tcn	shoulder
18-Nov-13	2	45.1	45.6	500	stp	btwp
18-Nov-13	3	4	5		lew	white line
18-Nov-13	3	0	50	3,000	f2	lane
18-Nov-13	3	28	30	200	a2	edgeline to shoulder
18-Nov-13	4	37	38		lew	white line
18-Nov-13	4	0	50	3,000	f2	lane
18-Nov-13	4	45.5	46.5		len	
18-Nov-13	5	0	50	2,800	f2	lane
18-Nov-13	5	2.1	3.3	300	sp	shoulder
18-Nov-13	5	16.3	17.6	500	sp	shoulder

Each condition file was examined and the crack data for each site for each year of the project was extracted, giving a large database in excess of 1,600 specific crack data files, from which to examine, identify and evaluate. Data was assimilated by site, with the cracking data sorted by year. A typical file is depicted in table 5.2.

Table 5.2 Cal23 crack data

Increasing		2006	2007	2008	2009	2010	2011	2012	2013
tcn	87	0	0	0	0	0	0	0	2,000
lew	104	0	0	0	0	0	0	0	1,000
agn	128	0	0	0	800	0	1,100	5,000	0
len	187	0	0	0	0	0	0	0	1,000
lww	195	0	0	0	0	0	0	0	1,000
tcw	245	0	0	0	0	0	0	0	5,300
tcw	246	0	0	0	0	0	0	0	400
tcw	248	0	0	0	0	0	0	0	200
tcw	249	0	0	0	0	0	0	0	300
tcn	250	0	0	0	0	0	0	0	250
lwn	252	0	0	0	0	0	0	8,000	8,000

This table shows the location (distance from site start) of each crack identified, the crack type and crack length for each year it was observed.

5.2.2 Evaluation of condition data

The state highway LTPP project started in 2001 and has 13 years of data for 63 sites. In 2003 an additional 81 local authority sites were added to the programme. During the 13 years of the project, sites have been removed and added for various reasons, the following sites have been eliminated or replaced:

- In 2006, three sites were removed due to realignment or reconstruction work. Cal50 was realigned and replaced with Cal50A, Cal32 full rehab was replaced with Cal61 and Cs2 increasing lane was lost due to the addition of a passing lane CS62. Cs28 realignment was replaced with CS60.
- In 2009, the four Christchurch and two Banks Peninsula sites were discontinued.
- In 2008, six Tauranga toll road sites were included.

Currently there are 145 sites in total.

Each site was analysed individually as follows:

1. Where a full rehabilitation has been undertaken on a site or a new site added the data was analysed both with and without the site start point reset to the project zero point (2001).
2. For the purposes of the LTPP programme cracks were classified as follows (table 5.3):

Table 5.3 Crack classification

Code	Description	Code	Description
LEN	Longitudinal edge cracks narrow	TCN	Transverse cracks narrow
LEW	Longitudinal edge cracks wide	TCW	Transverse cracks wide
LES	Longitudinal edge cracks sealed	TCS	Transverse cracks sealed
LWN	Longitudinal wheel cracks narrow	AGN1	Alligator cracks narrow (in wheel path)
LWW	Longitudinal wheel cracks wide	AGW1	Alligator cracks wide (in wheel path)
LWS	Longitudinal wheel cracks sealed	AGS1	Alligator cracks sealed (in wheel path)
LIN	Longitudinal irregular cracks narrow	AGN2	Alligator cracks narrow (outside wheel path)
LIW	Longitudinal irregular cracks wide	AGW2	Alligator cracks wide (outside wheel path)
LIS	Longitudinal irregular cracks sealed	AGS2	Alligator cracks sealed (outside wheel path)
PCW	Parabolic cracking wide	PCN	Parabolic cracking narrow
PCS	Parabolic cracking sealed		

However, to simplify the analysis for this research the crack types were reclassified to the three basic crack types: longitudinal, transverse and alligator. The rationale for this was as follows:

1. The longitudinal wheel crack was by far the most predominant of the longitudinal cracks. Longitudinal edge cracking had been observed at two or three sites and the longitudinal irregular cracks were usually confined to the edge of the wheel path. Often there was an overlap where the observed cracking could rightly be considered as wheel path or edge cracking, and only two or three sites where the longitudinal edge cracking could be directly attributed to edge failure and not due to wheel path loading.
2. Transverse cracks were predominantly confined to the wheel path and only two or three sites had what might be considered block cracking, where the crack had extended across one or more lanes.
3. The majority of the alligator cracks were confined to the wheel path.

4 Crack growth continued until a saturation point was reached and then individual cracks did not generally increase in length but in width. For the purposes of this research we tried not to distinguish between narrow and wide cracks.

5 The other phenomenon observed was that single transverse or longitudinal cracks would over time develop and form an area of alligator cracking. Where this had occurred and the individual crack growth within the alligator crack could be identified it was recorded.

6 The detailed nature of the database allowed specific cracks to be identified and the change in length or growth from year to year identified which in turn enabled a plot of the crack growth for individual cracks to be drawn from which the rate of change was obtained.

7 The total number of transverse longitudinal and alligator cracks for each site for each year was recorded and tabulated. From this the rate of growth or the number of cracks per year was obtained and plotted giving a growth table. Linear regression analysis was used to determine the rate of crack growth.

5.2.2.1 Site inclusion - exclusion

Sites were also eliminated from the analysis for the following reasons:

1 Sites with no cracking were identified and excluded from the analysis. This research was not intended to identify the onset of cracking but to follow its progression. However data is available which records the number of years before cracking developed and the sites where no cracking is present.

2 Sites with only one or two years of cracking data (2012–2014) were not included in the individual crack progression analysis, but were included in the cracked area progression.

3 The LTPP programme is representative of the entire New Zealand network, so it includes all pavement types – asphalt slurry seal and the most commonly used chipseal types. The 11 asphalt and two slurry seal sites in the programme were excluded from this analysis.

4 Sites with significant repair or patch work in asphalt, which then contained a significant portion of the site cracking were either excluded, or the cracking up till the time of the repair only was included. Note it was evident where patching occurred with asphalt that both the crack growth and the extent of the cracking developed at a different rate compared with chipseal cracking.

5.2.3 Determination of Individual crack growth

Cracks were divided into the three different categories: transverse, longitudinal and alligator, and the number of individual cracks within each category visually assessed and tabulated for each site and each year. The rate of growth in the number of cracks per site per year was calculated and plotted to establish the growth rate.

The following sites Cal12 SH5, Cal43 SH1, Cal49 SH1, and Akl3 Nielson St were selected to represent the three crack types and show individual crack length growth. These sites have had little or no maintenance and are relatively unaffected by other external factors that might unduly affect the crack growth. For this analysis, cracks were split into five groups, determined by their length. The groups were adjusted so that as near as possible there was an even number of cracks in each group. Then the average crack length for each group was calculated, followed by a calculation of the average crack growth rate of the cracks for each group. This data was then plotted with crack length (mm) for the x axis and crack growth (mm/year) for the y axis. The graphs, figures 5.5 to 5.9 define the growth rate for individual cracks.

5.2.4 Determination of total cracked area and cracked area growth

For each site the crack progression was followed from the time it was first recorded until the 2013/14 season or until it was repaired or sealed, and the crack lengths tabulated. The total cracked area was calculated by assuming a nominal width of 0.5m for cracks recorded as a unit length. Where cracks have both the length and width recorded (sections with multiple cracks covering an area wider than 0.5m) the area was calculated from the length and width dimensions. This data was then plotted, to show the crack size, for each crack, for each year, and then processed to show the following:

1 Crack number growth

Crack growth in terms of the number of cracks developing each year per site was calculated from the data in table B.1 of appendix B. The total number of cracks for each of the three crack classifications was determined and divided by the total number of sites giving the number of cracks per year per site.

2 Cracked area progression

The total cracked area for both the increasing and decreasing lanes and the combined area (sum of increasing and decreasing) was calculated and plotted to provide a visual means to review the crack area growth as well as identifying where major repairs or site changes may have occurred. This process was repeated for each site and for all sites combined.

3 Crack size versus crack life

The crack maximum length and how long it took to reach the maximum length was determined. Then the crack start date was set to year one (ie first year of the crack). The crack size was divided by the final size for each subsequent year, to give a percentage of the final size. Then an approximate crack size for the following times in its life – 0%, 25%, 33%, 50%, 67%, 75% and 100% – was determined. This provided the average for all the cracks on the site and created the plot % of crack life verse % of crack size. The goal was to see the growth rate of the crack as it developed, ie was it linear, or did it follow a different pattern of growth.

4 Crack growth rate

The crack growth rate determined in section 5.2 above was summarised for each of the three crack classifications using data from those sites which could be classified as either transverse, longitudinal, or alligator cracked sites. Furthermore the data from all sites was combined to provide crack growth rate independent of crack type. The crack growth rate graphs in section 5.2.7.3 show the average rate of growth of a particular crack with respect to crack size.

5.2.5 Identifying factors that affect crack growth

The data was further analysed to see if we could identify or correlate the crack growth to physical features. This was achieved by identifying the number of cracks associated with traffic volumes, speed environment, corners and drainage. For both the local authorities and state highways, the average number of cracks per site, and the total number of sites were identified (low site numbers can lead to outliers).

5.2.6 Detailed site inspections

1. Four of the sites listed in section 5.2.4 (Cal12, Cs13A, Cal34, and Cs55) were selected for detailed examination to see if trends over a shorter period could be identified. Site visits at approximately six-week intervals were made and all visible cracking recorded.
2. Individual crack growth as detailed in section 5.2.2 was undertaken.

5.2.7 Results

5.2.7.1 Determination of individual crack growth

Clearly with data from in excess of 100 sites it is not possible to present individual results from each site and so figures 5.1 to 5.3 present the combined site data while figures 5.4 to 5.9 are some selected results representative or typical of those obtained. Table B.1 in appendix B presents the total number of cracks divided into the three categories (transverse longitudinal and alligator) observed for each year the site was surveyed.

Crack number growth for all sites

Crack growth in terms of the number of cracks developing each year per site was calculated from the data in table B.1 of appendix B. The total number of cracks for each of the three crack classifications was determined and divided by the total number of sites giving the number of cracks per year per site. The relationship defining the number of cracks developing each year for local authority, state highway and all sites is presented below in figures 5.1 to 5.3. The fitted line highlights the observed trends.

Figure 5.1 Number of cracks per site per year, all local authority sites

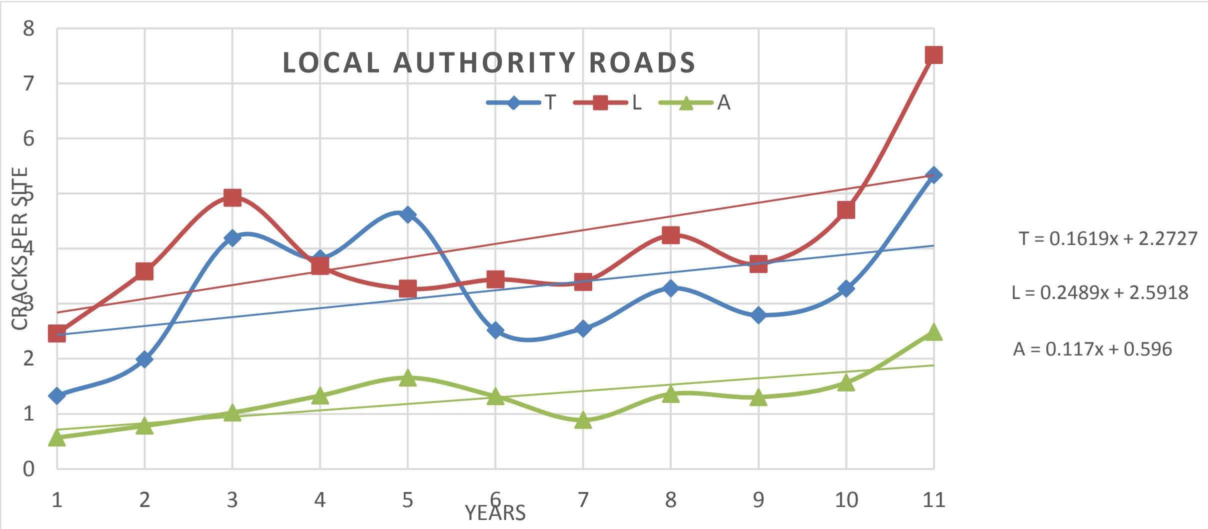


Figure 5.2 Number of cracks per site per year all state highways

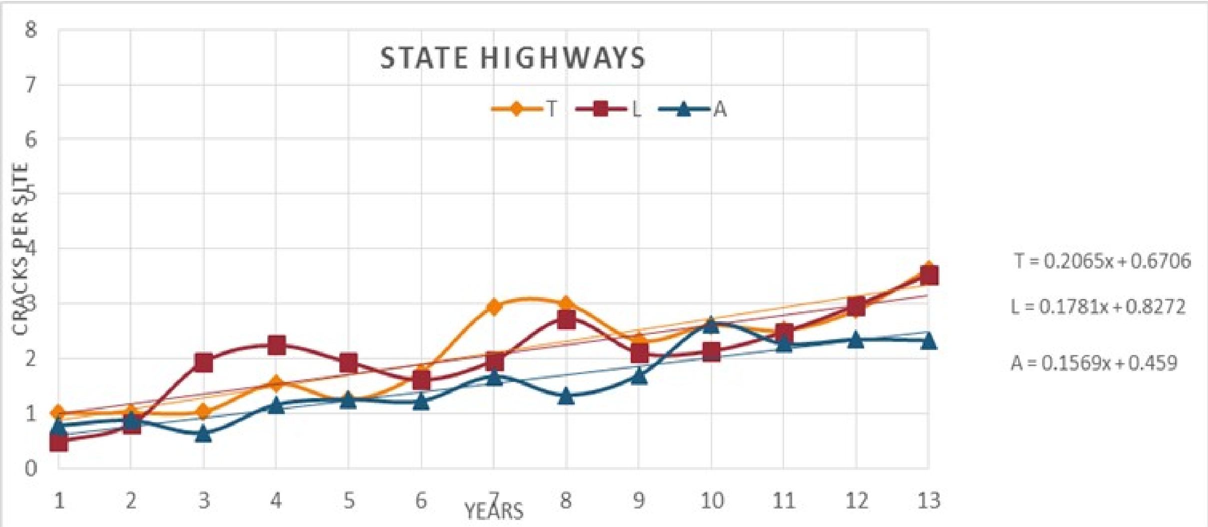
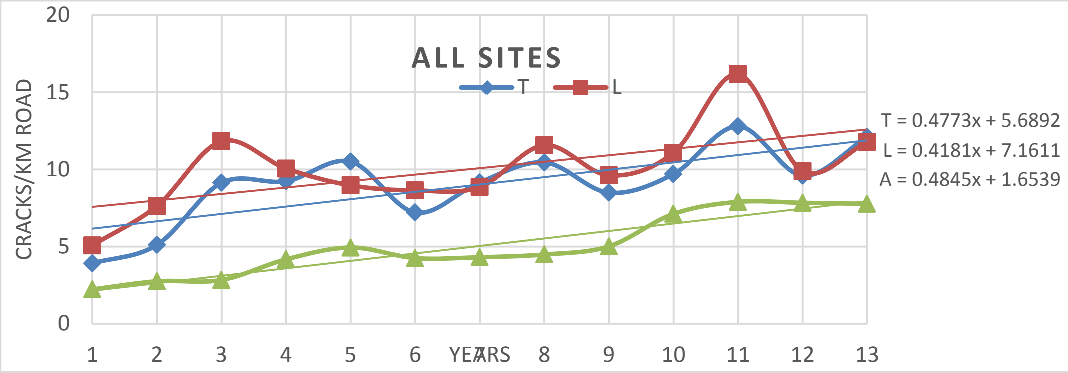


Figure 5.3 Number of cracks per km of road per year (all sites combined)



The peaks observed at three- or four-year intervals are maintenance related, where sites have either undergone some patching or full rehabilitation to repair the cracked area.

Individual crack length growth

Sites were selected which were considered representative of each of the three crack classifications for individual crack growth analysis.

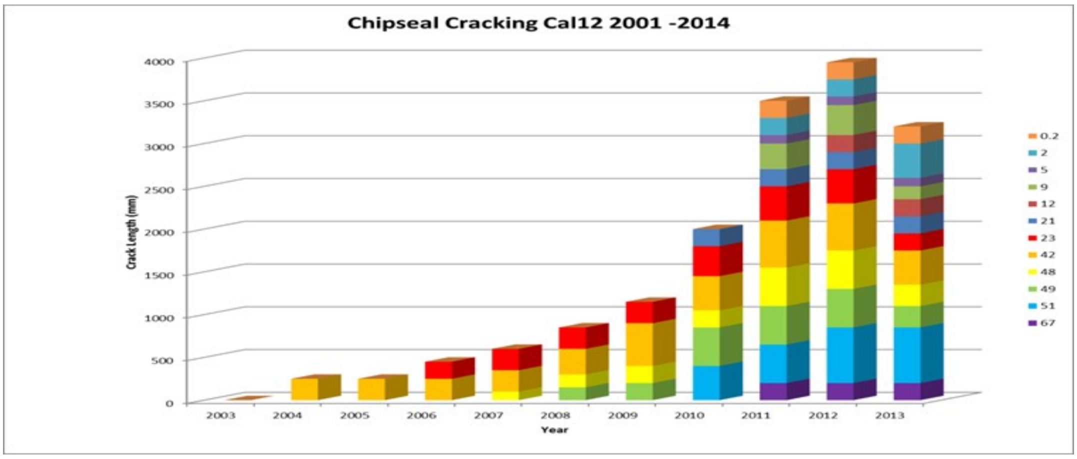
Table B.2 in appendix B presents the crack data from calibration site Cal12 on SH5 (Napier/Taupo). Cracking first started in 2004 and continued to increase until the site was resealed after the 2012 survey.

This site was chosen as an example of transverse crack growth, and is one of the few sites not affected by patch or repair work and clearly shows the growth of the transverse crack.

There is a gradual increase in both the number of cracks and the length of the individual cracks. A plot of the data is presented in figure 5.4. Note that in these figures a crack identified at the same location each year is represented by a particular colour. For example the light brown crack present from 2004 to 2013 is 0.2m from the site start. The red colour represents a crack located 23m from the site start and is present from 2006 to 2013. The height of each coloured box represents the crack length and so as a crack grows the height of the coloured box is increased.

This same notation is replicated in figures 5.6 and 5.8.

Figure 5.4 Cal12d transverse crack growth



The rate of crack growth was determined for three different crack sizes and is presented in figure 5.5. This reveals crack growth of 70mm/year, which is relatively independent of the crack size for this site.

Figure 5.5 Cal12d transverse crack growth rate

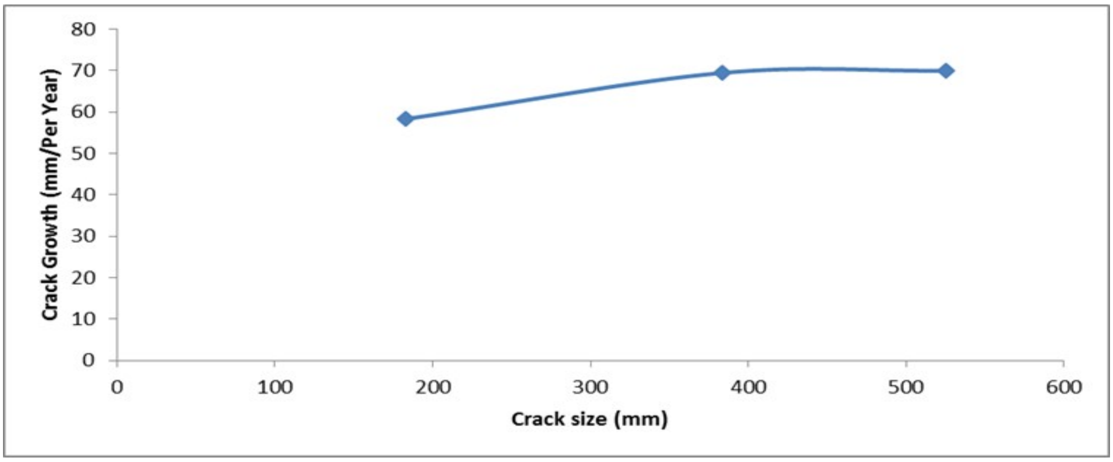


Table B.3 of appendix B lists the data presented below from Cal43 SH1 South Canterbury and is an example of a site primarily affected by longitudinal cracking. This site had a full rehabilitation after the 2011 survey.

Figure 5.6 Cal43 longitudinal crack growth

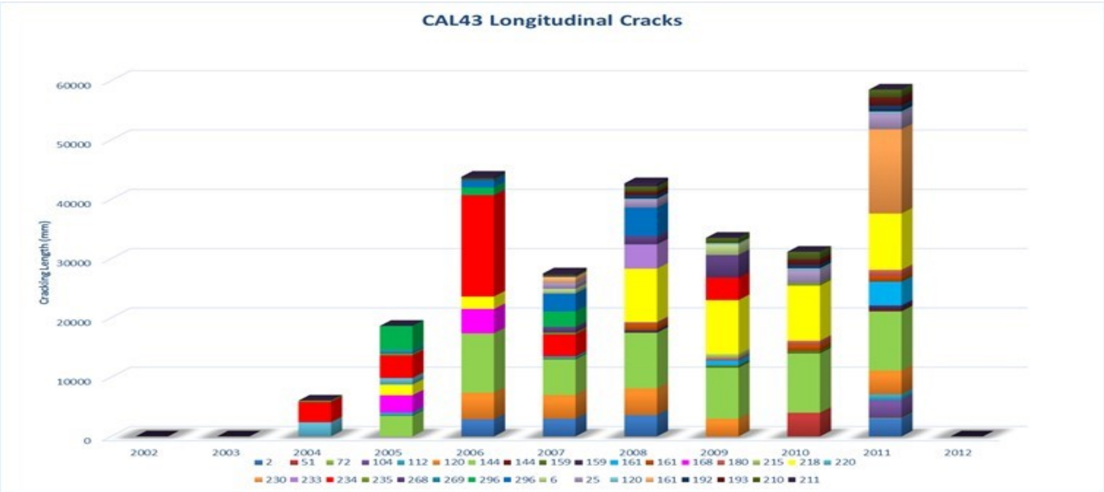
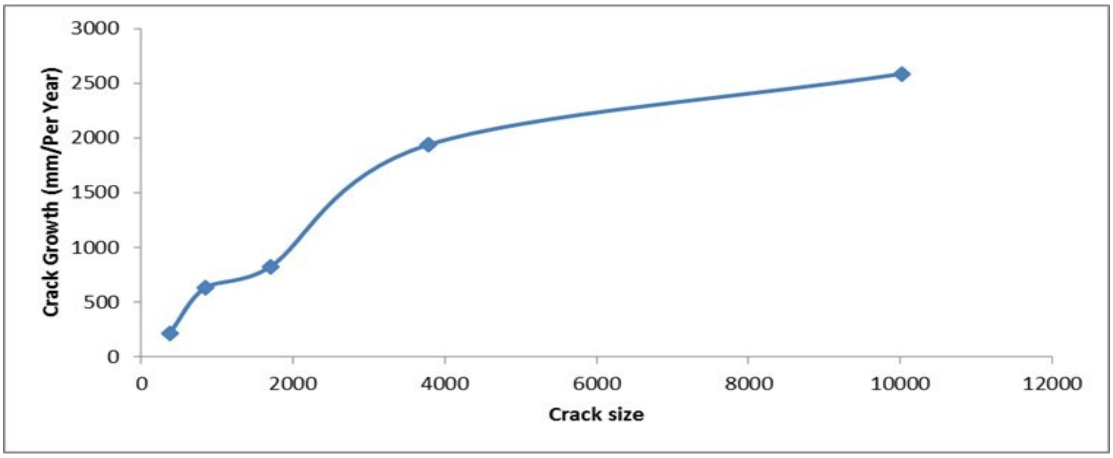


Figure 5.7 Cal43 longitudinal crack growth rate



Clearly there is a significant difference in both crack size and crack growth when compared with the transverse cracking example, with crack growth of up to 3,500mm per year. The true picture of the crack progression is somewhat distorted by the patch repairs undertaken in 2006 and 2008.

Table B.4 in appendix B details the cracking data presented below from AKL3 Nielson St Auckland, a site primarily affected by alligator cracking. This site has a large volume of heavy trucks and underwent a full rehabilitation in 2008. The data is presented here in figures 5.8 and 5.9.

Figure 5.8 AKL3 alligator crack growth

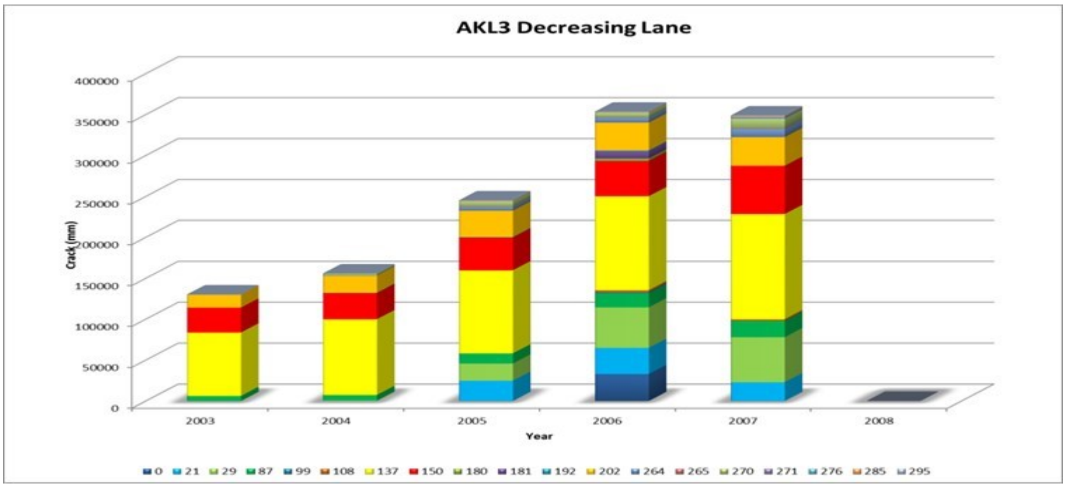
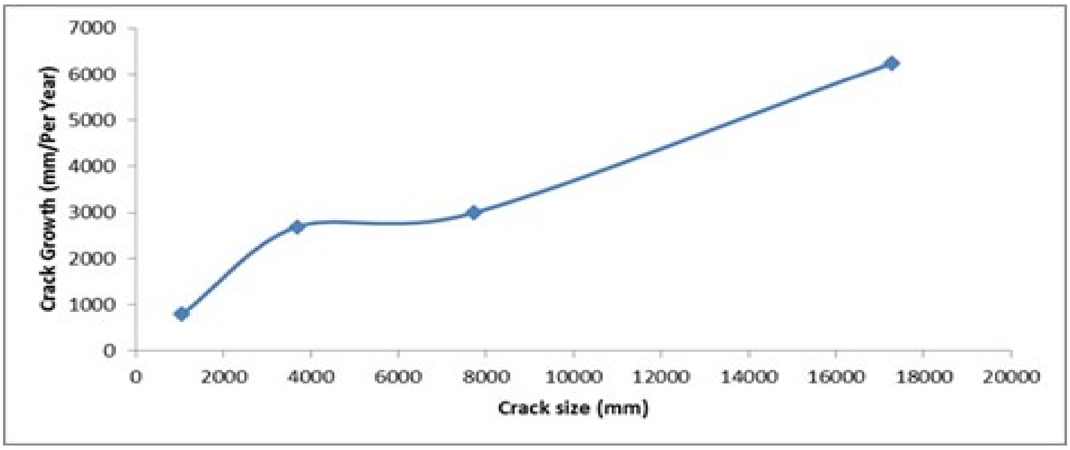


Figure 5.9 Akl3 alligator crack growth rate



Observations from the field and the review of this and other individual crack data

The width of the transverse crack is nominally dictated by the width of the wheel path and tends to grow to a maximum width (nominally around 800–1,000mm) quite quickly and then remain static. Transverse cracks rarely exceed 1,000mm and when cracking exceeds this width the crack usually forms part of a larger alligator cracked area.

There are two sites with block cracking where the transverse crack extends across the full lane and at both the block cracked sites often extend across the full road width.

Alligator cracking often starts as either transverse or longitudinal cracking or a combination of both.

Longitudinal cracks are often associated with deep rutting, or along the edge of a seal widening and or wheel path patch. This is observed more on the local authority sites where underground services have a significant influence on the presence of cracking.

5.2.7.2 Determination of total cracked area and cracked area growth

Individual sites

The total cracked area for the increasing and decreasing lanes and both lanes combined for each of the three representative sites is presented here in figures 5.10, 5.12 and 5.14.

The growth pattern, in terms of crack size versus crack life, shows how growth rate changes as the crack develops. This is presented in figures 5.11, 5.13 and 5.15 where the percentage of crack life is determined once the crack has reached its maximum length. The time in years taken from the point when the crack is first observed until the maximum length is observed is noted and then the percentage of the total length of the crack is plotted against the percentage of the time it took to reach maximum length.

Figure 5.10 Cal12 cracked area growth

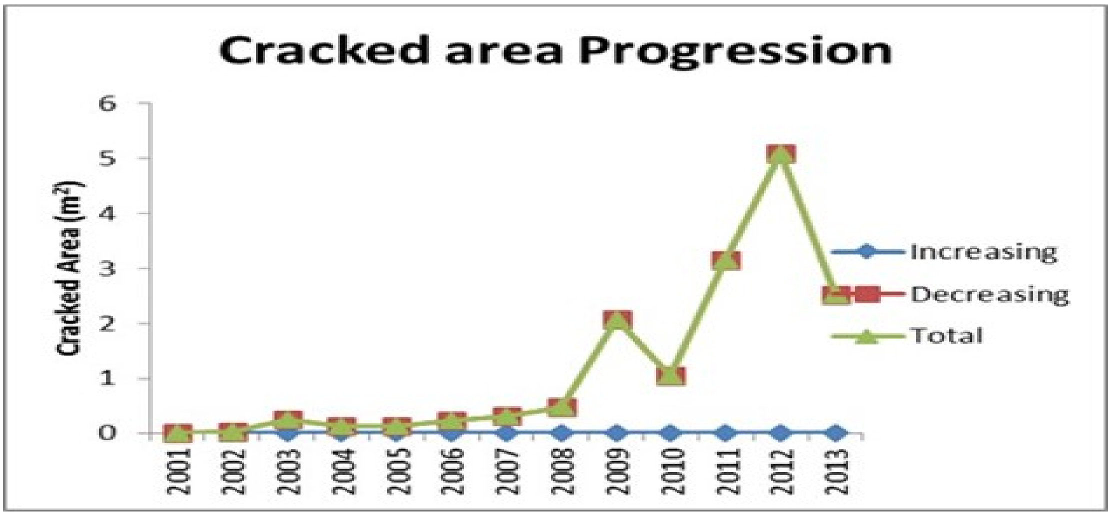
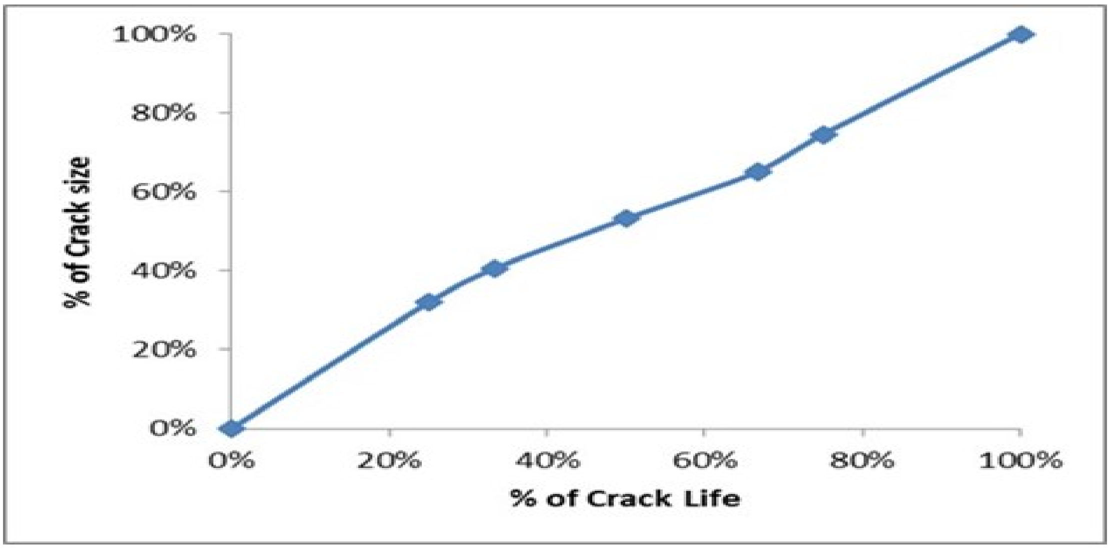


Figure 5.11 Cal12 crack growth as percentage of crack life



For this site (transverse cracking example) the cracked area growth increases exponentially after several years of low growth, whereas the crack size versus crack life is relatively linear.

Figure 5.12 Cal43 cracked area growth

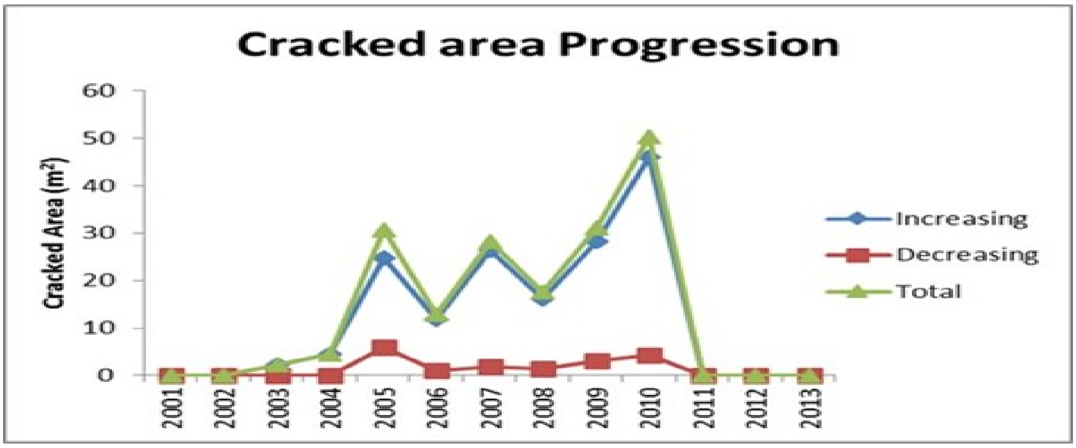
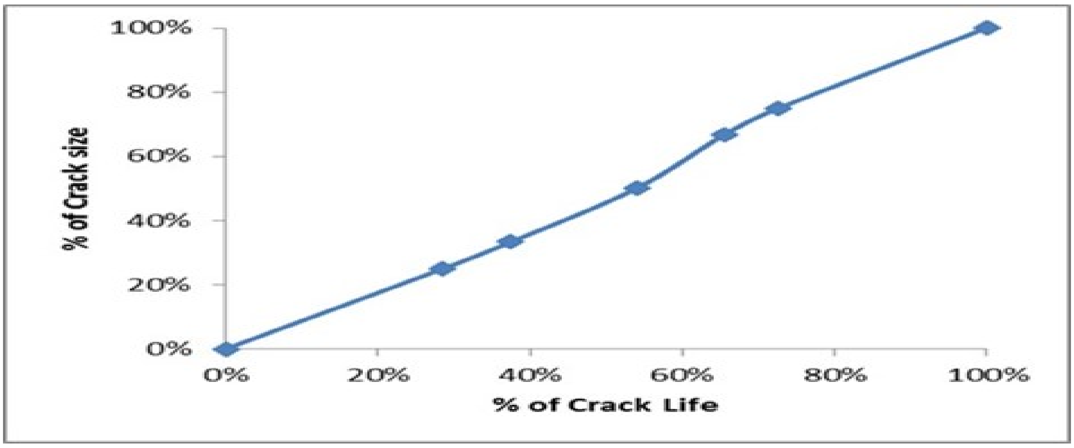


Figure 5.13 Crack growth as a percentage of crack life



For this site, Cal43, the cracked area growth has been affected by regular patching and repair work, reducing the peaks of 2005 and 2007 until the site underwent a full rehabilitation in 2010. The crack size versus crack growth for this site (predominantly longitudinal cracking) is also relatively linear, but has an increase midway through the cycle.

Figure 5.14 Akl3 cracked area growth

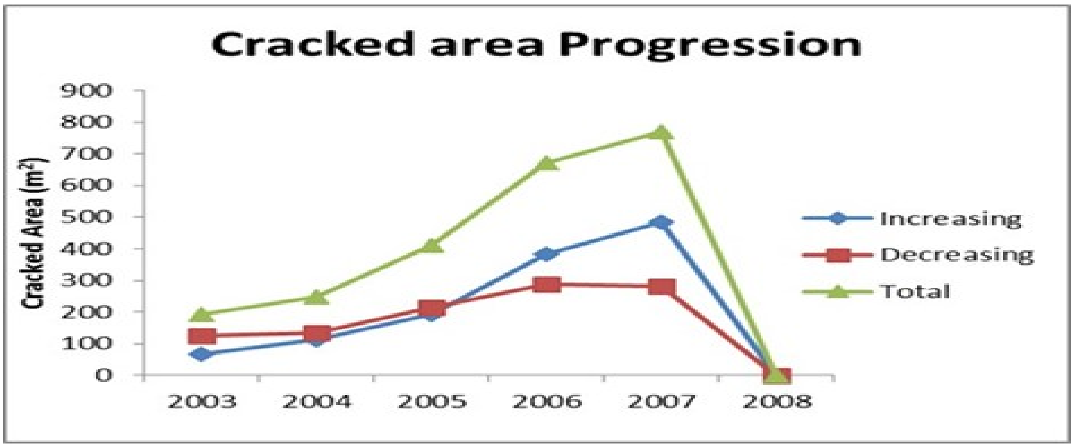
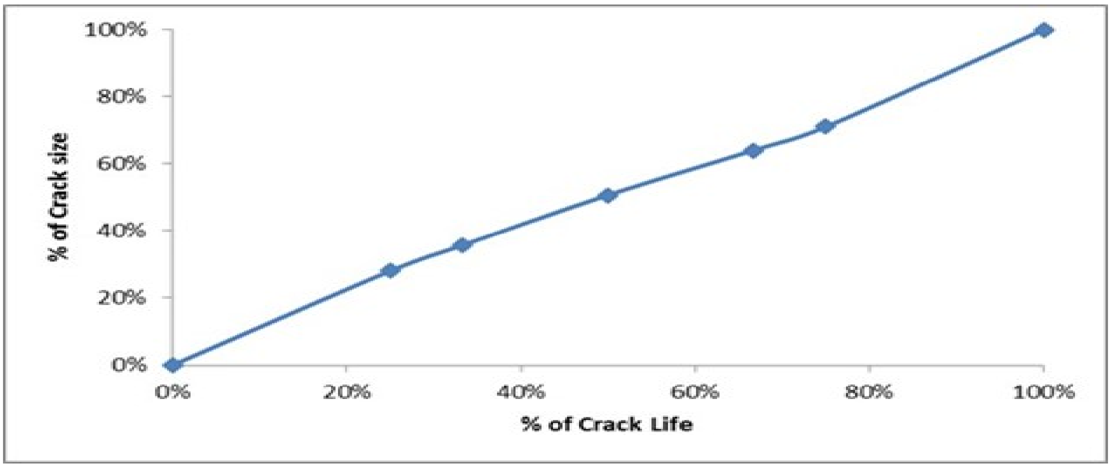


Figure 5.15 AKL3 crack growth as percentage of crack life.



This site, Akl3, is predominantly alligator cracking and shows there is a levelling off of the total cracked area in the decreasing lane (figure 5.14) which suggests that a saturation point may have been reached where the severity of the cracking may increase but not the total cracked area. The crack size versus crack life plot is very similar in shape to that for the transverse crack example, and this may be due to the fact that at both of these sites the failure mechanism is predominantly structural with associated rutting in the wheel path.

5.2.7.3 Crack growth rate

Figures 5.16 and 5.18 present the total crack length observed each year for all state highway and local authority sites respectively. The total cracked length data is further divided into the three crack categories.

Figures 5.17 and 5.19 show the crack growth rate in mm/year for different crack lengths for state highway and local authority sites respectively.

State highways

The results appear to highlight the maintenance strategies that are followed. Alligator cracking is not allowed to develop over a long period and has undergone consistent repair work every three or four years, longitudinal cracking appears to have a six year repair cycle, and transverse cracking up to eight or nine years possibly to coincide with the reseal cycle.

All three crack types have similar growth rates, although it appears that initially the longitudinal crack growth rate is higher, reducing once the crack length exceeds 8m.

Figure 5.16 Total cracked length observed on state highways for each year from 2001 to 2014

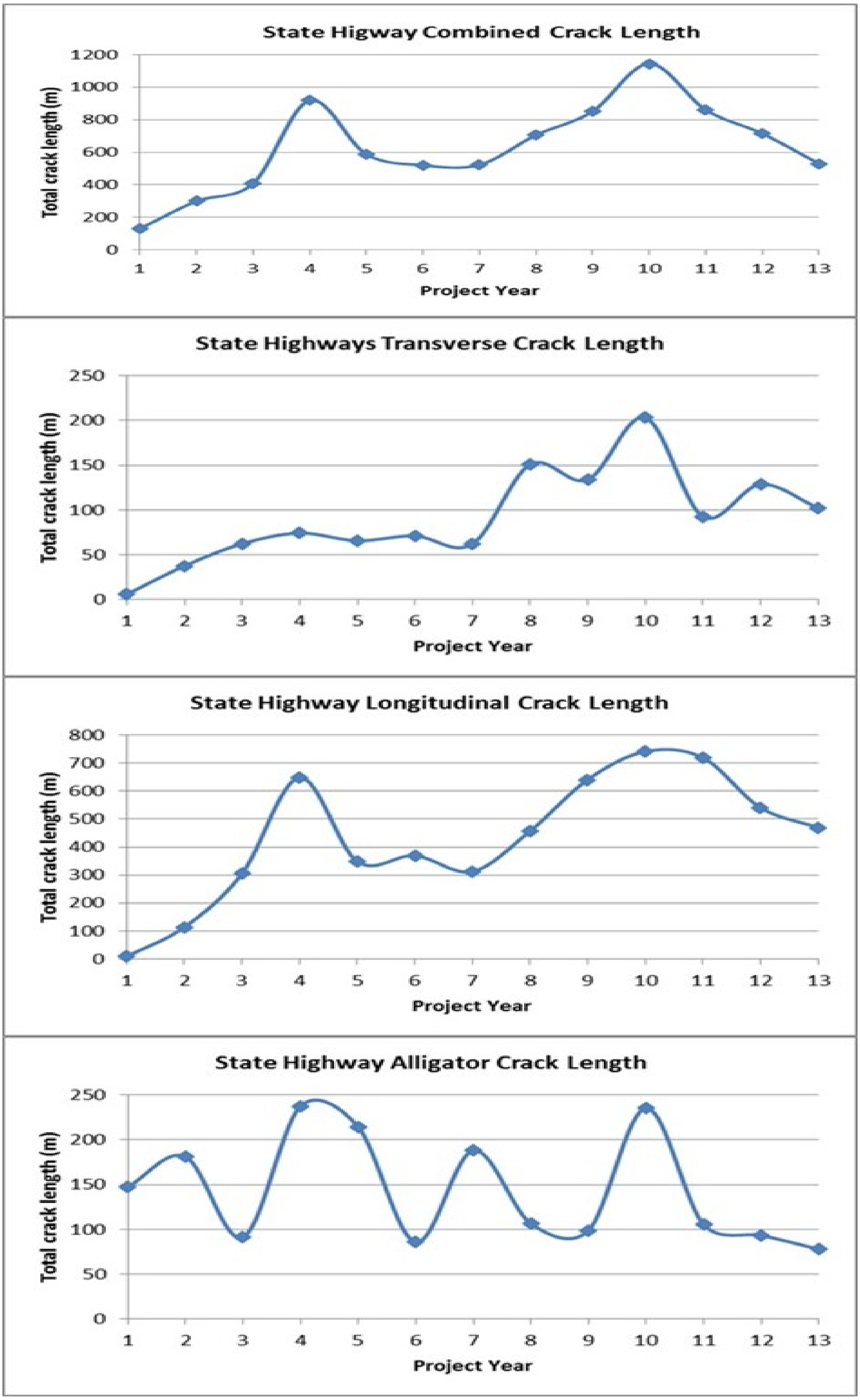
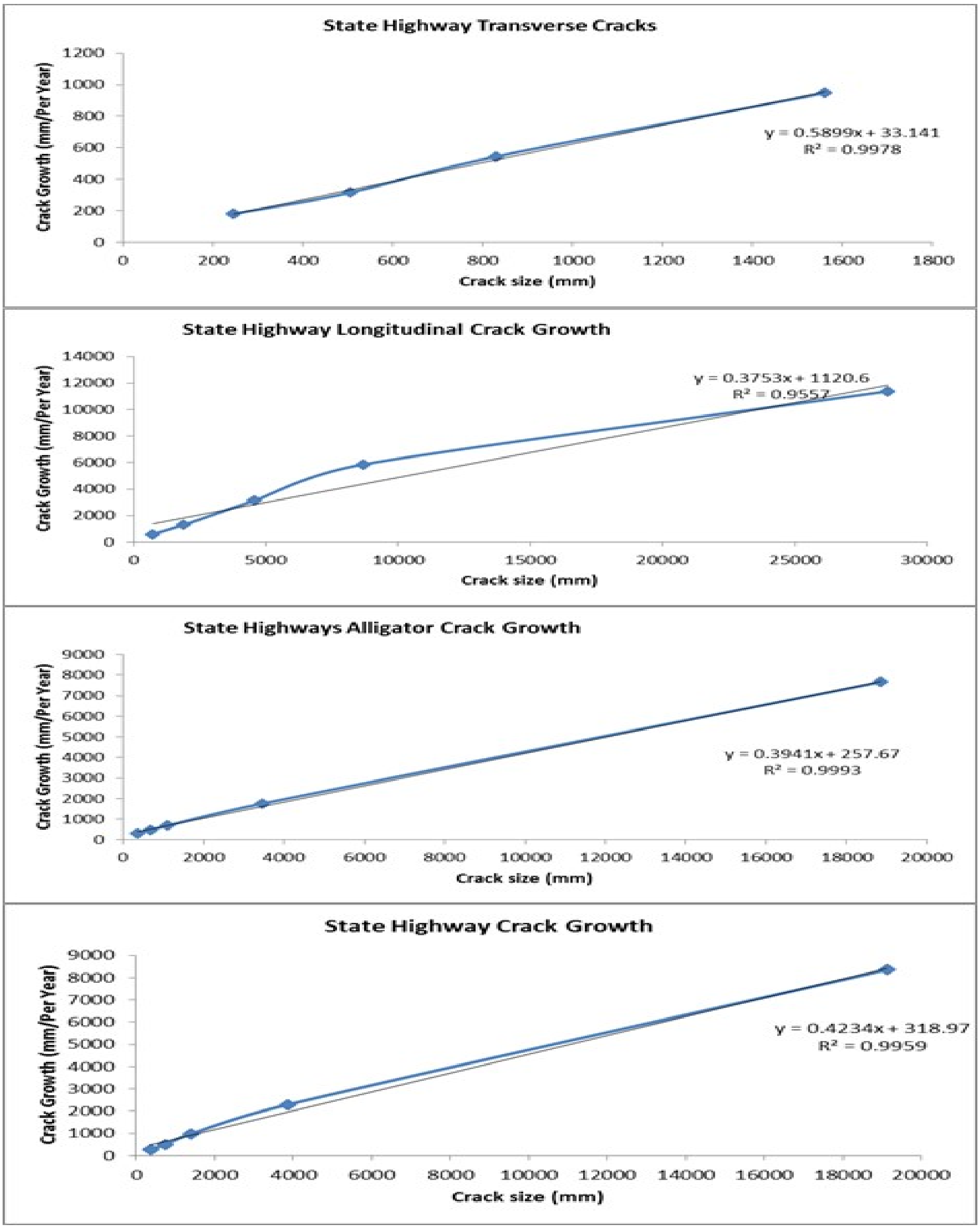


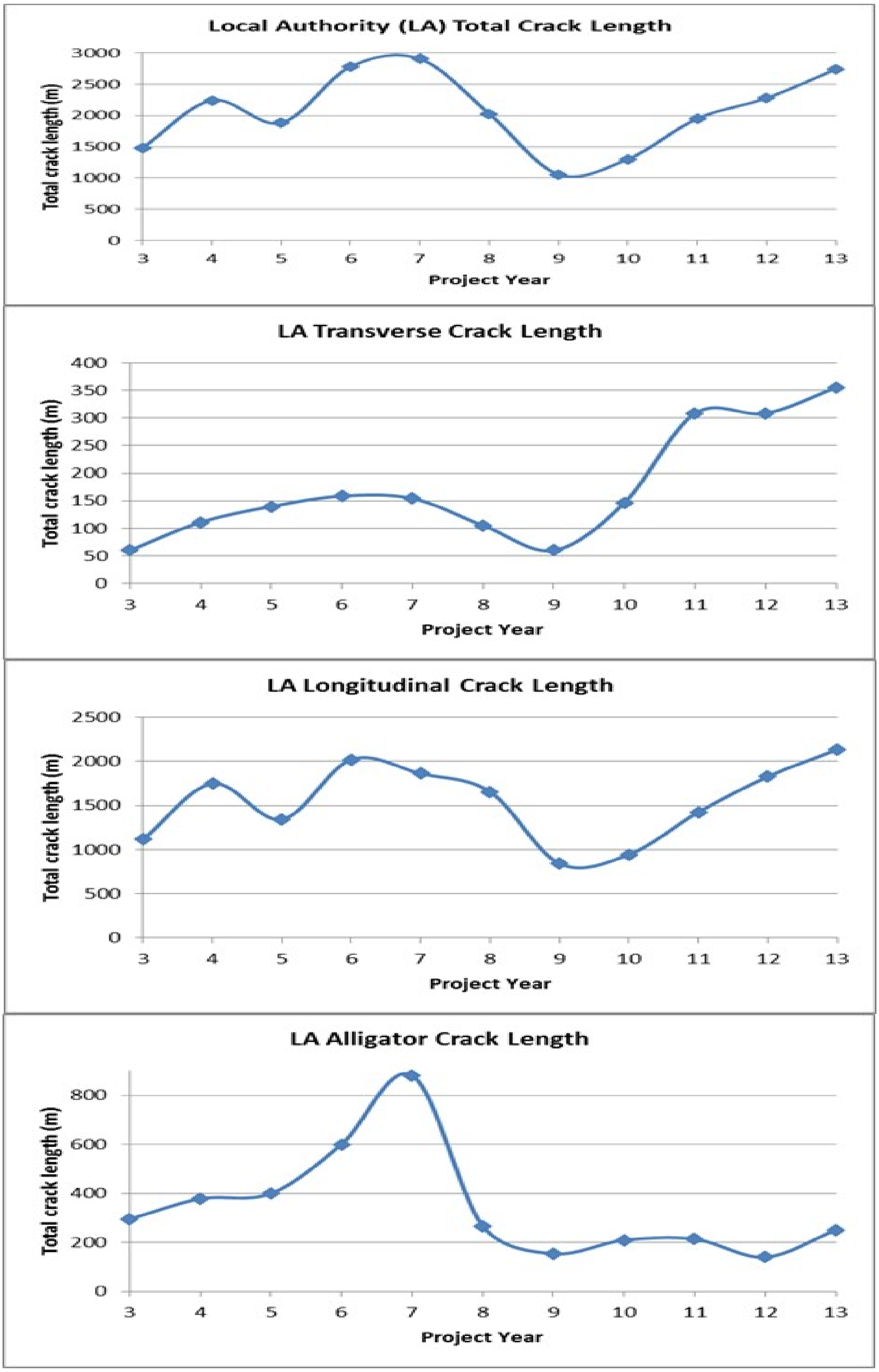
Figure 5.17 State highway crack growth rate



Local authority sites

Figure 5.18 presents the total crack length observed each year for all local authority sites.

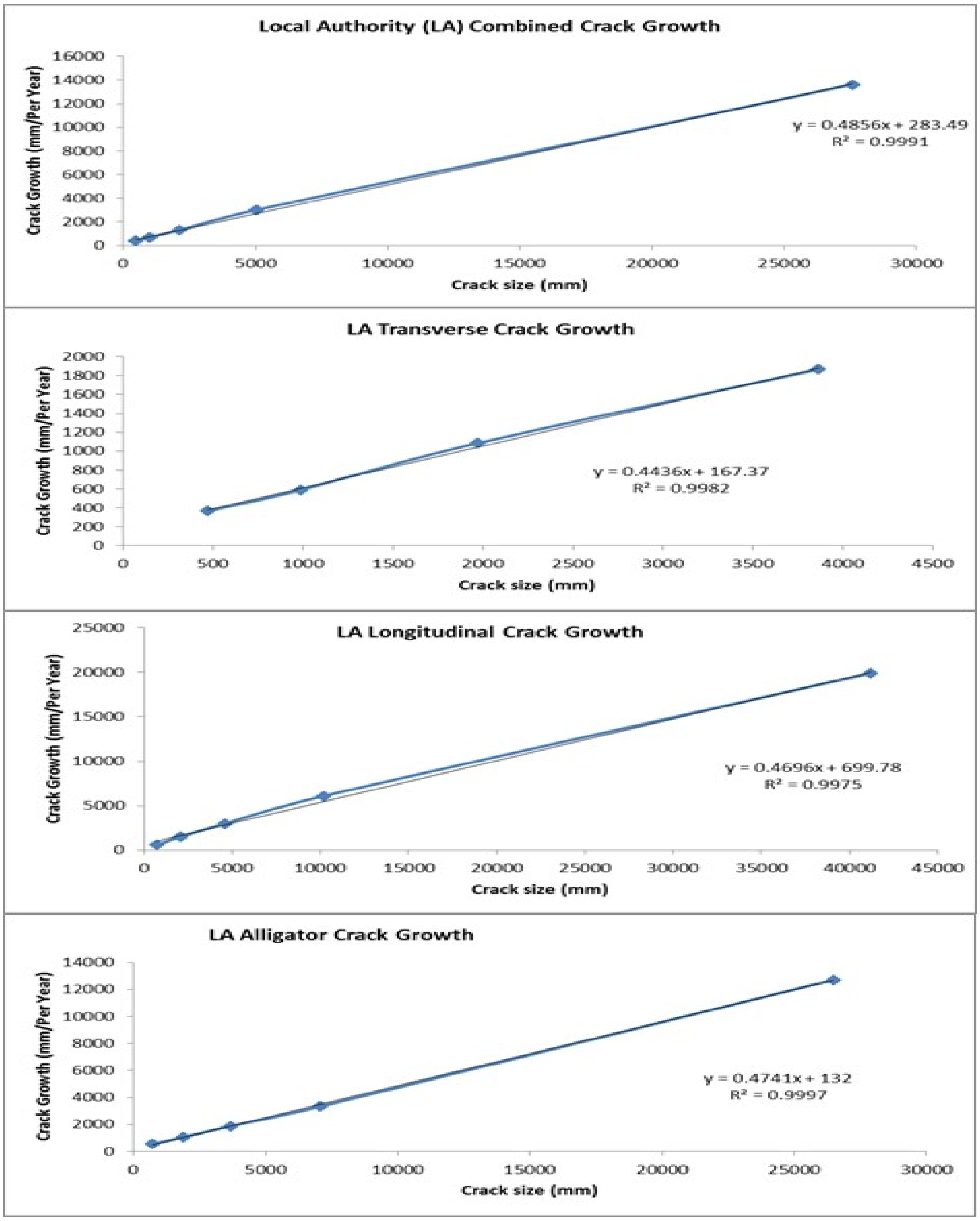
Figure 5.18 Total crack length local authority sites 2003–2014



Initially there is no obvious pattern on the local authority sites with the total crack length reamining fairly constant, a pattern that might be expected on sites with lower volume traffic. However if the maintenance undertaken on these site is taken into account it becomes clear how this has affected the results.

Site AKL3, which contained the bulk of the alligator cracking for the local authority sites, underwent a full rehabilitation following the year seven survey. Three of the Dunedin sites had a significant portion of the longitudinal and transverse cracking and were resealed after the year eight survey. The effect of the reseal in Dunedin was short lived as most of the cracking returned after two years. If we take these factors into account then both the transverse and longitudinal cracks show a steady increase with time while the alligator cracking remains fairly constant. Figure 5.19 shows the crack growth rate on the local authority sites.

Figure 5.19 Crack growth in mm per year for cracks of different length



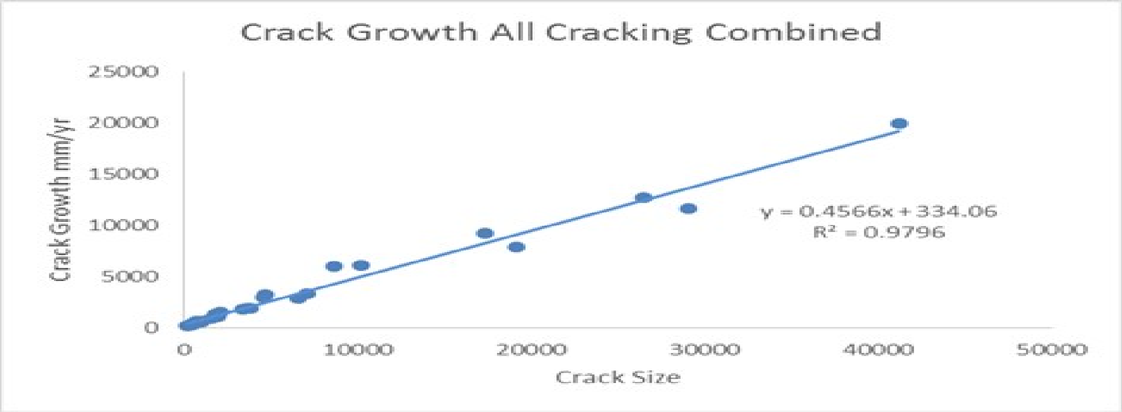
The crack growth in mm/year is relatively constant regardless of the crack type and is at a rate which is approximately half the crack size, and crack growth for the state highway sites is lower than that of the local authority roads.

State highways: **crack growth (mm/year) = 0.4234*crack length (mm) + 318mm**

Local authority roads: **crack growth (mm/year) = 0.4696*crack length (mm) + 699mm**

Figure 5.20 shows the crack growth rate in mm/year versus crack size for all sites combined.

Figure 5.20 Crack growth rate all sites combined



All sites combined: crack growth (mm/year) = 0.4566*crack length (mm) +334mm

5.2.8 Identifying factors that influence crack growth

Table 5.4 below lists the number of cracks per site and the number of sites associated with each of the environmental factors: traffic volume, speed environment, corners and drainage.

The average number of cracks per site, and the total number of sites were identified for both the local authorities and state highway calibration sites. Note the kerb and channel drainage and speed environment for state highways have low incidence numbers and may not be representative of these factors.

Table 5.4 Environmental factor effects

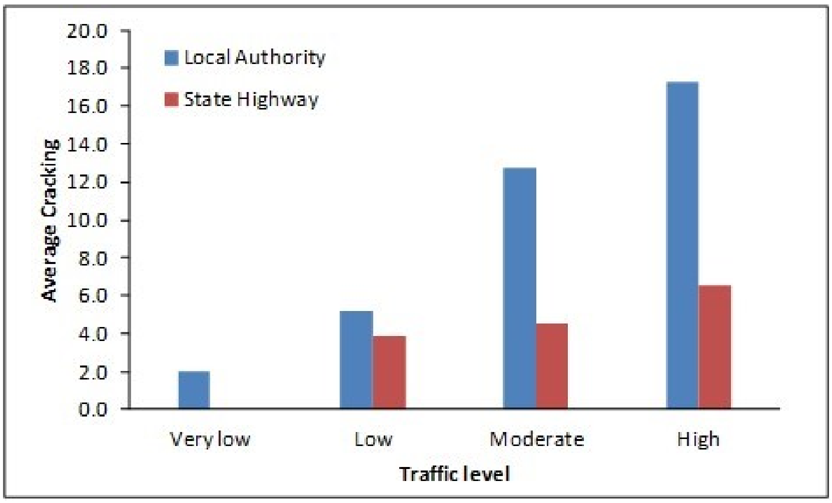
Local authority roads														
Environmental factor	**Traffic**				**Speed**			**Corners**				**Drainage**		
	Very low	Low	Moderate	High	Low	Moderate	High	Straight	Slight	Tight	Kerb	Good	Average	Bad
Cracks per site	2.0	5.2	12.7	17.3	11.5	7.7	7.2	8.6	9.8	1.6	11.2	7.0	10.1	8.6
No. of sites	7	36	21	10	25	18	29	42	27	4	25	26	32	16
State highway roads														
Environmental factor	**Traffic**				**Speed**			**Corners**				**Drainage**		
	Very low	Low	Mod	High	Low	Moderate	High	Straight	Slight	Tight	Kerb	Good	Average	Bad
Cracks per site		3.8	4.6	6.5		4.3	4.6	4.0	6.4		2.8	4.6	3.1	8.3
No. of sites		21	25	14		3	56	44	15		2	22	26	11

It is clear that cracking is present for all environmental factors considered and the local authority sites have considerably more cracking than the state highway sites. The following points are noted.

Traffic volume

The number of cracks per site increases with increasing traffic volumes. The moderate and high volume local authority sites have a significantly higher increase than that for state highways at the same traffic volume (as shown in figure 5.21). A comparison between local authority cracking against state highway cracking for moderate traffic level and high traffic level showed statistically significant differences between local authority sites and state highway sites (t-test p-value = 0.015 for moderate traffic level and t-test p-value = 0.053 for high traffic level). This suggests that the local authority sites are not designed for the higher volume traffic.

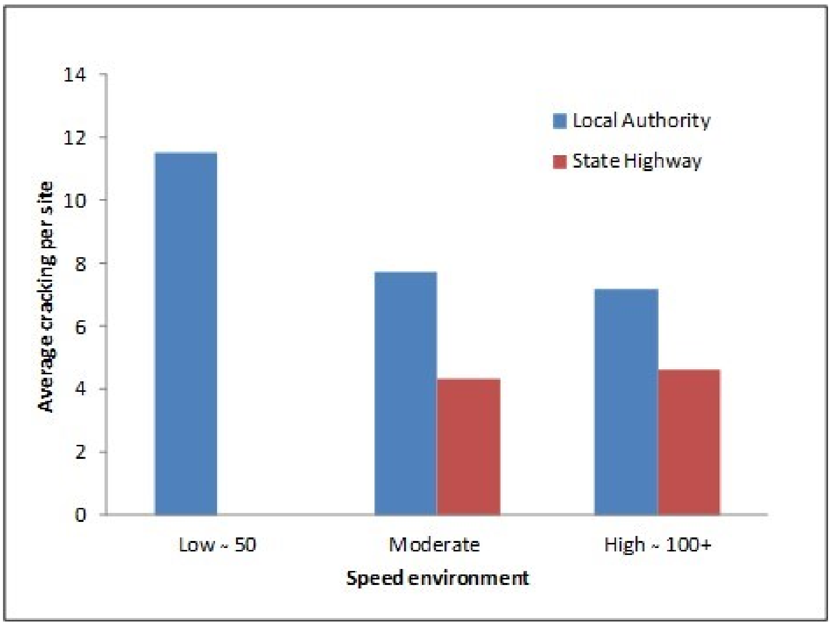
Figure 5.21 Average cracking vs traffic level



Speed environment

There is insufficient data to make conclusive comparisons on how the speed environment influences the state highway sites, but it would appear that it does not significantly influence cracking. On the local authority sites the low speed sites have more cracking than the moderate and high speed sites (shown in figure 5.22). Underground services where there are a lot of seal joint cracks are the most likely cause for this increase as they are more predominant on the 50km/h sites. Analysis of cracking at high speed environment showed there was a significant difference in average number of cracks per site between local authority sites and state highway sites (p-value = 0.090).

Figure 5.22 Average cracking vs speed environment



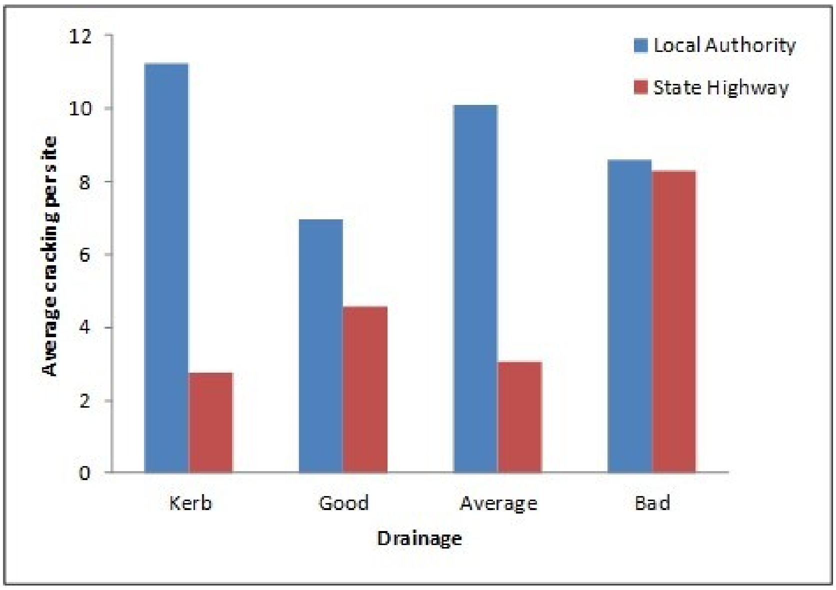
Cornering

It appears that tight corners reduce the number of cracks on local authority sites, where cracking on straight sections is significantly higher than cracking on tight corners (p-value < 0.000). Cornering on the state highway sites increases the probability of cracking.

Drainage

Interestingly the local authority kerb and channel sites are the poorest performers with the most cracking, as shown in figure 5.23. On the state highway sites there is an increase in cracking for bad drainage only.

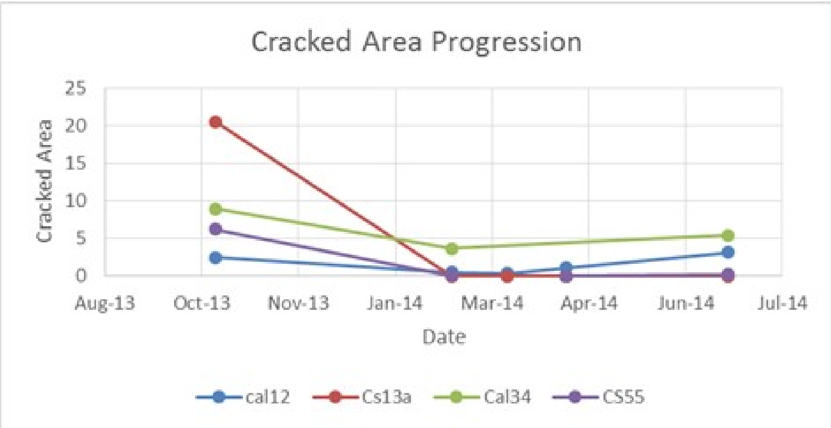
Figure 5.23 Average cracking per site vs drainage



5.2.9 Detailed site inspections

Four sites (Cal12, Cs13A, Cal34 and Cs55) were selected for detailed examination to see if trends over a shorter period could be identified. Site visits at approximately six week intervals were made and all visible cracking recorded.

Figure 5.24 Detailed cracked area growth



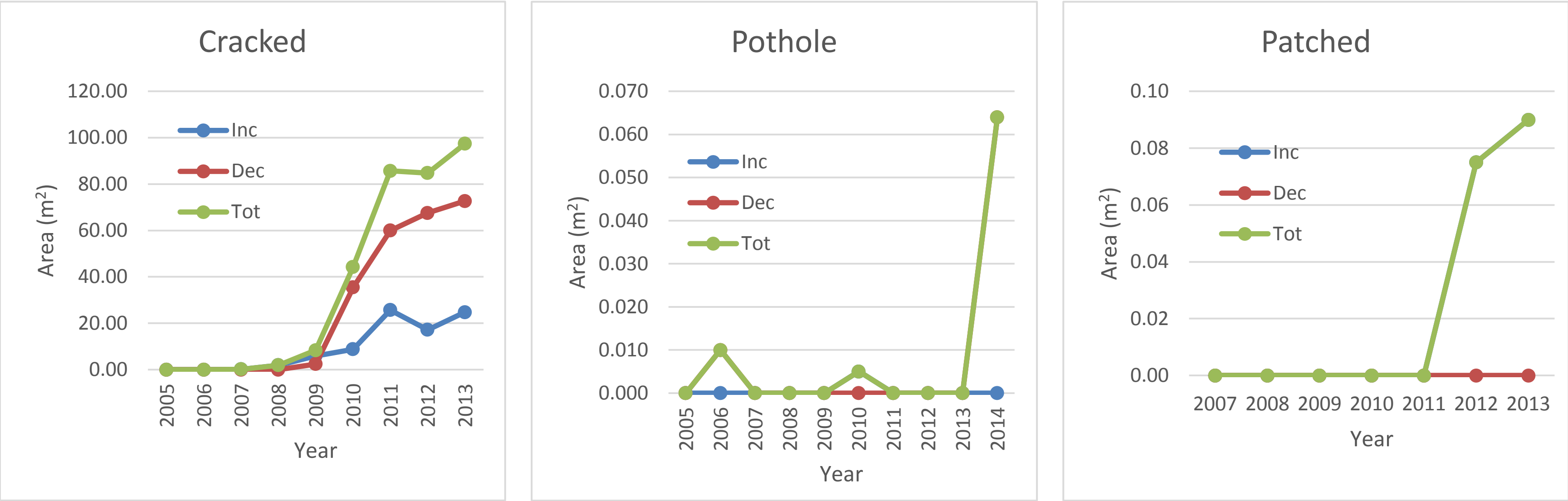
It is clear from figure 5.24 above that cracking reduces over the summer as temperatures rise softening the binder and then increases as winter sets in and temperatures drop. All four sites have varying degrees of flushing with CS13a being the most flushed. Field observations indicate the cracks are still present but are covered by the excess binder which flows into and seals the cracks. At site Cs13a there is evidence of underlying cracking even though the surface is not cracked.

5.2.10 Cracking – influence on rutting, roughness, potholes and patching

Some preliminary analysis was also undertaken to examine the relationship between the formation of cracking and the rate of development of patching and or potholing and roughness and rutting. The results to date from this analysis are presented here.

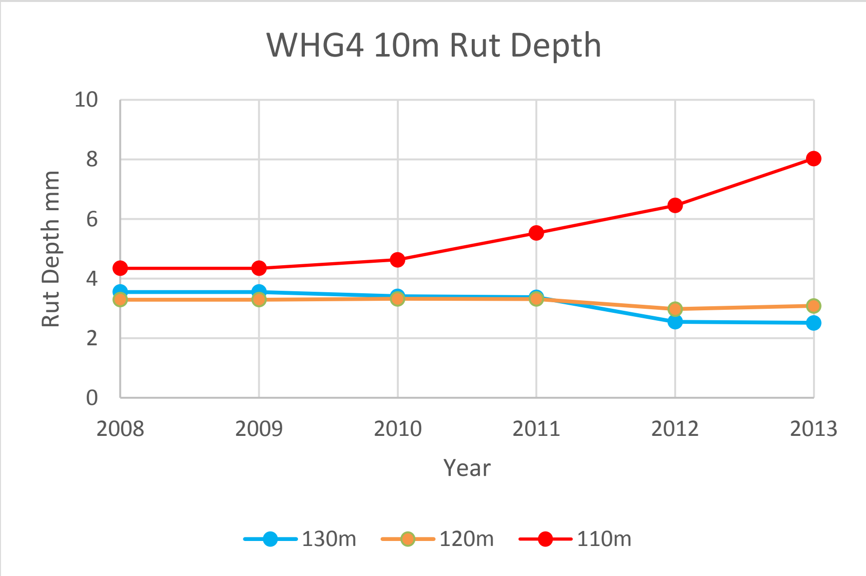
The cracking, patching and pothole data from local authority site Whg4 and state highway site Cal43 has been analysed to determine if there is scope for further analysis to better define these relationships.

Figure 5.25 Whg4 cracked area pothole area and patched area



Reviewing the information presented in these figures suggests that three years after cracking has commenced, either potholes develop or patching has been implemented. Furthermore it is clear that cracking is evident for two or three years before there is an obvious change in the roughness and rutting characteristics. investigation into the roughness and rutting on this section has identified trends which suggest that there is some inter-relationship between increased rut formation and increased roughness developing after the observation of the crack as shown in figure 5.26. In figure 5.26 both rutting and roughness can be seen to increase at a greater rate in the 110m rutting and 120m roughness sections from 2010 onwards.

Figure 5.26 Whg4 corresponding roughness and rutting



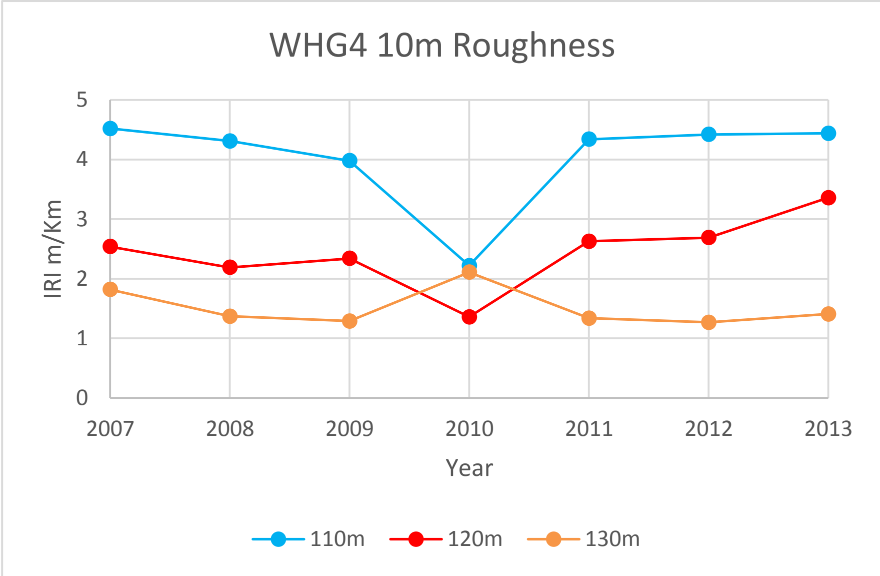


Figure 5.27 Cal43 cracked area pothole area and patched area

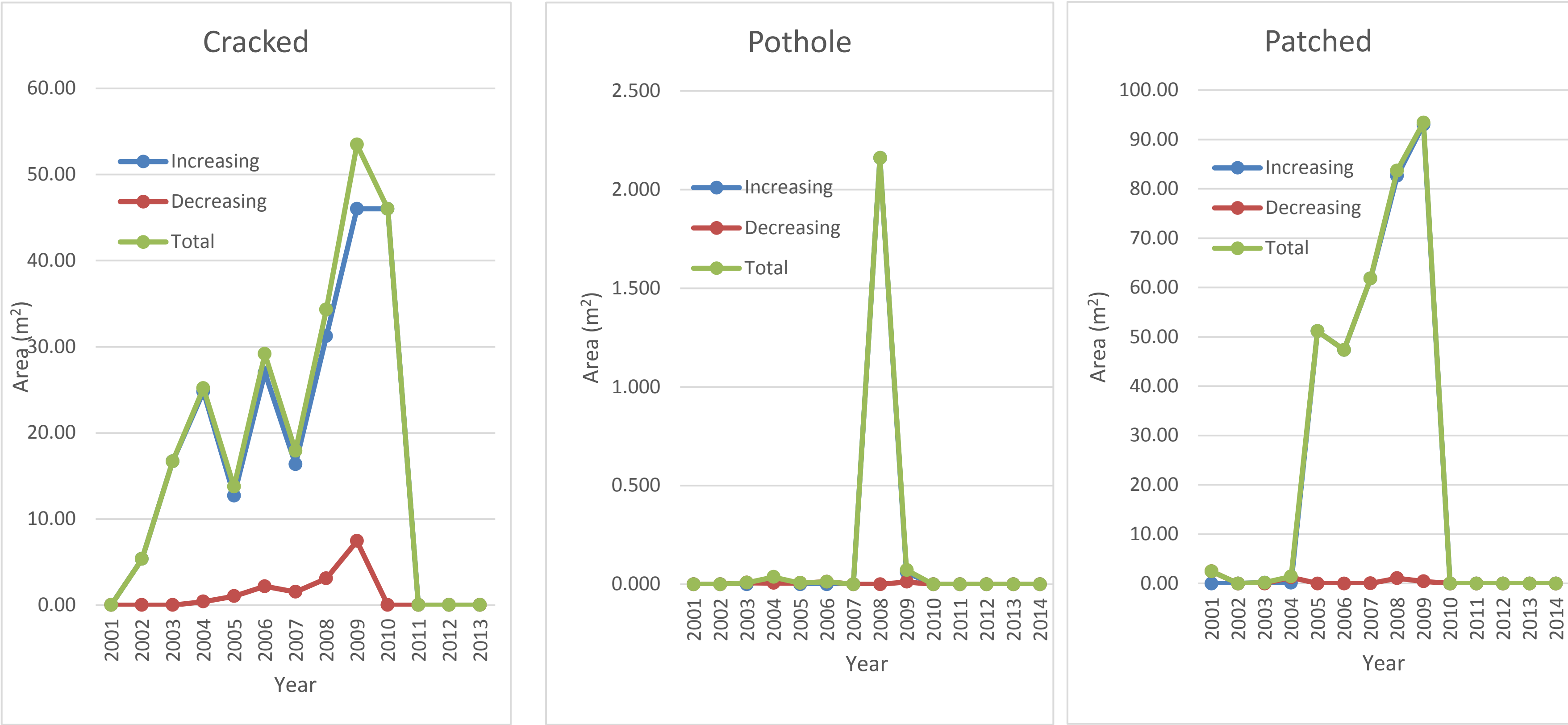


Figure 5.27 shows the same trend on state highways as displayed on Whg4, that three years after cracking has commenced, either potholes develop or patching has been implemented.

Note this analysis should be extended to include all sites so that a more definitive result can be confirmed.

5.2.11 Conclusions

The results in the previous section provide some clear information on crack growth in both the state highway and local authority environments.

Figures 5.1, 5.2 and 5.3 show the number of cracks that could be expected to develop. The peaks and troughs in these figures can in the main be attributed to maintenance.

Transverse crack growth rate: Number of cracks/km of road = 0.4773(years since initiation) +5.7

Longitudinal crack growth rate: Number of cracks/km of road = 0.4181(years since initiation) +7.2

Alligator crack growth rate: Number of cracks/km of road = 0.4845(years since initiation) +1.7

The average crack growth for the three different crack types investigated for both state highways and local authority roads is provided in figures 5.16 to 5.19. Figure 5.20 shows the average annual increase in crack length is approximately half the crack length, so as the crack grows the rate of crack growth in mm/year, increases.

Combined crack length growth: Crack growth mm/year = 0.4566*crack length +334mm

There is some evidence which shows that on flushed sites cracks self-seal over the warmer summer period but more research is needed to determine if this affects pavement life significantly.

Clearly there is scope for more detailed research and analysis of this data to further progress the understanding of crack growth. Additional research could include:

- More detailed analysis of the environmental factors and how they influence crack growth. Data on pavement strength should also be included in this environmental analysis.
- There has been no attempt to quantify the time taken for cracking to commence nor the effect of excess binder on crack progression. It is clear from site observations where the excess binder has been removed that there is underlying cracking, but it is not clear how this affects pavement life.
- It would also be appropriate to subdivide the longitudinal cracking into three categories (edge cracks, wheel cracks and cracking outside the wheel path) to see if there is variation within these different longitudinal crack types.
- Crack growth for block cracking has not been included and warrants some investigation.
- There has been no attempt to divide the sites into urban and rural and clearly there are differences between these two where underground services play a significant factor in the type of cracking present.

6 Cracking maintenance practices

Chipseal surfaces have long been used as an economical surfacing option providing satisfactory waterproofing capability for road pavements. While much effort is put in to achieving appropriately designed seals, changes in traffic conditions, environmental conditions and material performance over time eventually results in the failure of a seal. Chipseal defects such as cracking and flushing are two of the most prominent maintenance drivers. In order to ensure that chipseal pavements are able to function adequately, it is vital that timely and appropriate maintenance is undertaken. This report presents analysis investigating the maintenance requirements of chipseals to achieve a longer lasting, well-performing pavement network.

6.1 Context for this chapter

This chapter aims at answering the question of 'When do maintenance engineers need to be concerned about cracking?' More specifically the research scope has identified three specific questions for this chapter, including:

- What is the proportion of resurfacing that is conducted as a result of flushing versus resurfacing as a result of cracking?
- Under what circumstances would the deferral of resurfacing be an option given different degrees of cracking?
- What are the life-cycle cost implications related to deferring the resurfacing of cracked surfaces? It may be possible to save some money by deferring resurfacing but ultimately costs may be significantly higher in the future if all these sections have to be rehabilitated?

There are a few instances where cracking alone is the primary driver for major maintenance interventions such as resurfacing and/or rehabilitation. In most cases, cracking alone would be considered a routine maintenance requirement. Once cracking occurs in conjunction with other defects it becomes a resurfacing or rehabilitation consideration. Yet, the point at which cracking and other defects warrant maintenance is not a clear decision point. There are a number of issues to consider when cracking is used as an input into maintenance decision including:

- What type and extent of cracking occurs on the sections under consideration?
- Is cracking the primary defect or does it occur as a secondary defect to a different defect such as rutting?
- Does the cracking originate from the pavement or is it purely a surface defect?
- Is there an active growth of the cracking?
- Does the cracking result in a significant compromise of the surface integrity?

This section investigates some existing practices and data in order to provide more concrete guidance of when maintenance becomes an option once a surface starts to crack.

6.2 Existing guidelines and research work on maintaining cracked surfaces

6.2.1 Guidelines

There is strong consensus regarding the type and causes of cracking (refer to table 6.1). The guidance as to when to intervene on a cracked road is not well documented. The three maintenance options suitable to address cracking are:

- routine maintenance or crack sealing
- resurfacing, or
- rehabilitation.

Table 6.1 Crack type and common causes (Austroads 2006)

Crack types for reporting		Description	Common causes	Load-related or environmental	Surface or structural
Summary	Detailed				
Linear	**Longitudinal**	Linear cracks that run longitudinally along the pavement. They can occur singly, or in groups as a series of parallel or echelon cracks. Some limited branching can occur. These cracks are usually associated with moisture related subgrade movements which generate stresses near the edge of bituminous pavements. If in the wheel path, longitudinal cracks can indicate load related distress, and may be an early stage of interconnected cracking.	**When occurring singly:** Reflection of joint or shrinkage crack over cemented base, poorly constructed joint in asphalt surfacing, displacement of joint at pavement widening. Reflection of joints from road widening. Poor work practices. **When occurring as a series of near-parallel cracks:** Volume change of expansive clay subgrade (shoulder cracking), cyclical weakening of the pavement edge (shoulder cracking), differential settlement between cut and fill. Reflection of crack from underlying cemented subbase. **For rigid pavements**: Lateral shrinkage due to excessive slab width; shallow longitudinal joint. Differential settlement; longitudinal joint too close to traffic lane; inadequate slab thickness. Poor work practices.	Usually environmental, and can be load-related (especially if located in a wheel path).	Structural
	Transverse	Unconnected linear cracks running across the pavement, usually occurring in bound flexible pavements and rigid pavements. They can occur singly, or in groups as a series of parallel cracks.	Reflection of a shrinkage crack or joint in an underlying cemented base, construction joint or shrinkage crack in asphalt surfacing (due to low temperature or bitumen hardening), differential settlement between cut and fill, structural failure of Portland cement concrete base. Normal shrinkage; shrinkage of slab during curing as a result of sawing joints late or excess slab length. Inadequate slab thickness; slab rocking.	Usually environmental	Structural
Inter connected	**Block (polygons generally >300 mm)**	Interconnected cracks forming a series of blocks approximately rectangular in shape, usually distributed over the whole pavement. This type of cracking is usually reflective cracking associated with bound flexible pavements and rigid pavements.	Reflection from joints, shrinkage effects or fatigue in an underlying bound (cemented) or macadam layer. Inadequate slab thickness. Loss of subbase / subgrade support. Settlement of subgrade. Ageing, hardening and thermal effects in bituminous surfacing.	Environmental or load-related.	Structural
	Crocodile (polygons generally <300 mm)	Interconnected or interlaced cracks forming a series of small polygons resembling a crocodile skin. Also sometimes referred to as alligator cracking, polygon cracking or crazing. They may have a noticeable longitudinal grain. Primarily associated with traffic and usually confined to the wheel paths.	Fatigue induced structural cracking, high pavement curvature value. Inadequate pavement thickness, moisture in formation, inadequate pavement or surfacing materials (e.g., brittle or aged bitumen or under-strength aggregates), lack of compaction in pavement layers or subgrade.	Load-related	Structural
Crack types for reporting		Description	Common causes	Load-related or environmental	Surface or structural
Summary	Detailed				
Irregular	**Meandering**	Unconnected irregular cracks varying in line and direction, and usually occurring singly. They are primarily associated with moisture related subgrade movements inducing stresses in bituminous pavements.	Moisture weakening of the pavement. Subgrade drying/shrinkage from tree roots. Reflection of shrinkage cracks from bound base. Inadequate slab thickness; rocking; settlement. Shrinkage of slab during curing as a result of sawing joints late or excess slab length. Underground service or settlement at a structure (bridge/culvert).	Usually environmental, and can be load-related.	Surface or structural
	Diagonal	Unconnected cracks running diagonally across the pavement, usually occurring in rigid pavements.	Age hardening of bitumen. Shrinkage of slab during curing possibly due to excessive slab length or late sawing of joints. Reflection of underlying joint. Underground service settlement or at a structure (bridge/culvert); inadequate slab thickness; slab rocking. Tree roots.	Usually environmental.	Structural
Irregular	**Crescent shaped**	Also sometimes referred to as half moon shaped cracking. Commonly associated with shoving and often occur in closely spaced parallel groups. Usually associated with asphalt surfacings.	Poor bond causing slippage between wearing course and underlying layers, thin wearing course, dragging by paver when laying at low temperatures, high stresses due to braking and acceleration movements, poor quality asphalt work, low modulus base course.	Load-related	Surface
	Corner and edge cracking	Cracking across the corner or near an edge of a rigid slab. Related to subgrade or subbase support failure beneath the rigid base.	Inadequate slab thickness; loss of subbase / subgrade support.	Load-related	Structural

Source: Austroads (2006)

Crack sealing is recommended in most cases where the ingress of water is of concern for a road length. The Transport Agency recommends chipsealing as an option for hairline cracks (<1mm wide) and when less than 5% of the surface is affected by the cracking. Where active crack growth is observed a stress absorbing membrane is advised (Transit NZ 2005). The Austroads guideline (2006) recommends rehabilitation for cracking exceeding 15% and roughness IRI > 6m/km.

According to the South African guidelines resurfacing will only be considered if the crack extent reaches threshold levels but all defects are only associated with surface failures. If cracking occurs in conjunction with structural deficiencies, a rehabilitation options is considered (Jordaan 2006).

6.2.2 Status of current knowledge base

The NZ dTIMS pavement management system was initiated during 1999. One of the outcomes from the project development was a composite index (Surface Integrity Index-SII) that gives the overall health of the surface (Fawcett et al 2001). The SII is used for the triggering of surface options when it exceeds certain threshold levels (refer to table 6.2). The primary driver for the SII is cracking; however, given its strong age-related composition, there are strong correlations between the SII and all surface-related defects.

Table 6.2 Trigger levels used for resurfacing (NZTA 2013)

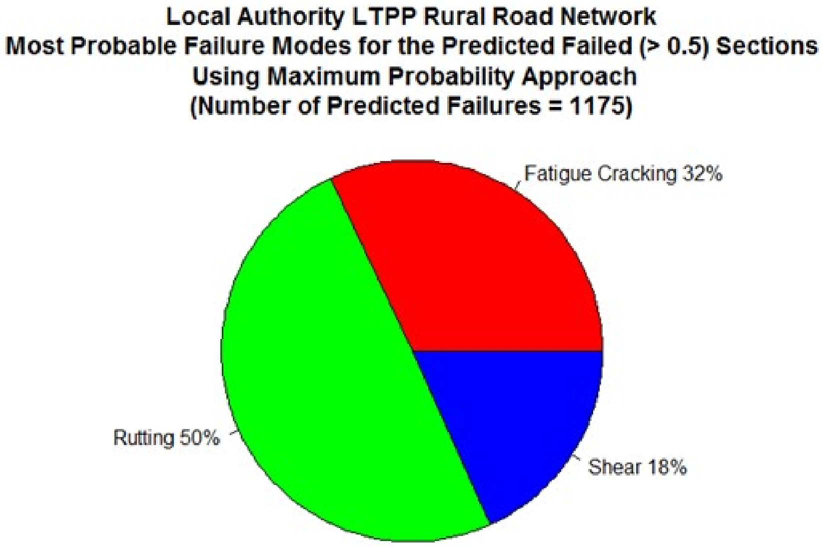
Trigger	National strategic	National strategic – HV	Regional strategic	Regional connector	Regional distributor
FGROUP	**1**	**2**	**3**	**4**	**5**
SURF_SII	10	10	10	20	25

In her PhD research, Schlotjes (2013) developed a risk index that forecast the probability of a pavement section going into accelerated failure given a number of loading, climatic and composition characteristics. The failure probability is calculated on the basis of three main defects including cracking, rutting and shear. The contribution of each defect towards the overall failure probability is calculated based on a number of possible failure mechanisms for each defect. Figure 6.2 depicts the potential failure paths for a pavement undergoing accelerated failure as a result of cracking. The factors that mostly contribute towards fatigue cracking failures are (Schlotjes 2013):

- traffic loading
- composition
- strength
- environment
- surface condition
- subgrade sensitivity.

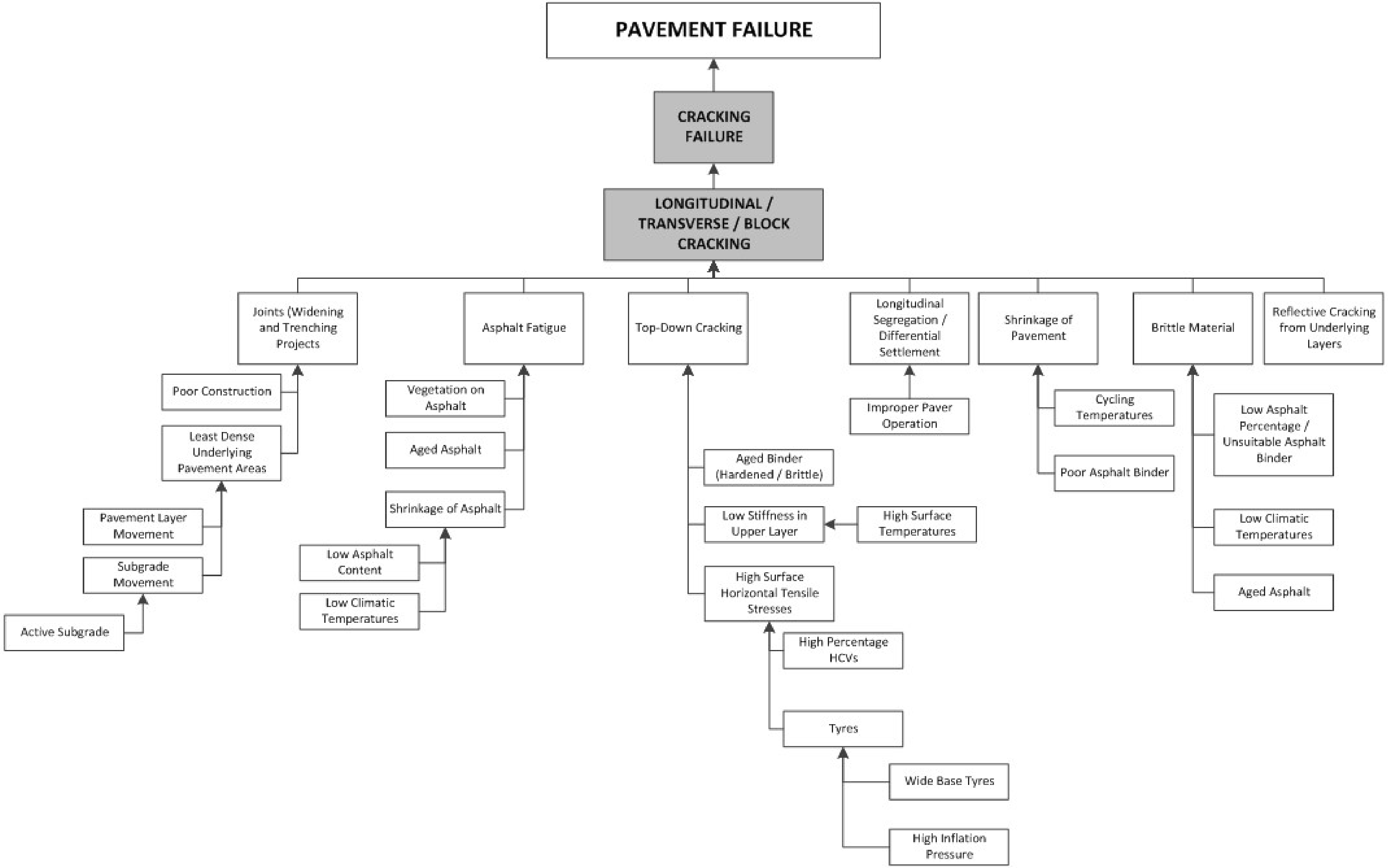
The failure probabilities that contributed mostly towards failure of the rural road LTPP dataset are summarised in figure 6.1. This figure shows the proportion of the failure modes contributing towards failure of the LTPP sites. It can be seen more than half of the sites fail due to rutting, approximately 30% fail due to cracking and the remaining 20% fail due to shear. Note there are secondary failure modes that were not considered in this graph. Therefore it is unknown what portion of roads has failed due to a combination of cracking and rutting.

Figure 6.1 Proportion of maximum failure probabilities for primary failure modes



Source: Schlotjes (2013)

Figure 6.2 Failure chart for cracking failure (Schlotjes 2013)



In his research, Roux (2014) investigated the progression of road roughness by considering the different wavelengths in isolation. During the model development all factors were investigated for a potential correlation with both roughness and roughness progression rate. From all of these there was only a slight correlation with cracking on the roughness progression rate on only the E3 (2 to 4m) wavelength (refer to table 6.3).

For all practical purposes the correlation was small enough to conclude that cracking does not impact much on the development of roughness.

Table 6.3 Correlations greater than 0.2 with *e1* to *e6*

With *de1*	Correlation	With *de2*	Correlation	With *de3*	Correlation
diri	0.460	diri	0.593	diri	0.605
drut	0.231	drut	0.296	drut	0.346
				dcrk_pct	0.209
With *de4*	**Correlation**	**With *de5***	**Correlation**		
diri	0.550	diri	0.399		
drut	0.336	drut	0.320		

Source: Roux (2015)

6.3 Maintenance intervention on New Zealand state highways

In order to develop a better understanding of network intervention levels, the 2013 national analysis of the state highways was analysed. The outputs provided in this section summarises the cracking status during the timing of treatments on the state highways. Note that these levels do not represent the cracking intervention points as the maintenance options were undertaken for an array of reasons. Therefore the outputs simply indicate the crack status prior to and after maintenance was undertaken, regardless of the reasoning behind doing the maintenance.

Two figures are presented: figure 6.3 depicts the distribution of actual crack percentages on the state highways for sections that were identified for maintenance within the next year, and figure 6.4 shows the probability of cracking for sections identified for maintenance within the next year on the state highways.

Figure 6.3 shows the actual crack percentages of the state highway sections identified for maintenance within the next year. Note the scale of the box and whisker plots was adjusted for this graph given the small percentages of cracking on the roads. Observations from this figure include:

- There is an order of magnitude difference between the cracking for chipsealed resurfacing sections compared with the asphalt concrete (AC) resurfacing projects. This suggests cracking to be much more of an issue on AC surfaces compared with the chipseal surfaces.
- It is also evident that the rehabilitation sections have a significant amount of cracking with percentages as high as 22%. It is therefore safe to assume that most rehabilitation sites have a high amount of cracking associated with them.

Figure 6.4 does not show actual cracking, but it does indicate the likelihood of a section being cracked at the stage of maintenance. More important to observe from this figure is the likelihood of cracking directly following the respective maintenance option. Based on experience it is expected to start noticing cracking occurring on sections that has a crack initiation probability above 0.3. With that in mind, the observations from the figure are:

- It is noticeable that the crack probability on AC surfaces is significantly higher than the chipseal surfaces. This observation also correlates with the actual crack extent presented in figure 6.3.
- The reset of crack probability for the resurfaced section is relatively high. This correlates well with research findings and actual observations where some surfaces display cracking almost instantaneously following a resurface. It is particularly notable where there is a thick layer of historical surfaces (Henning et al 2006).
- The probability of cracking prior to rehabilitation is high. One can therefore safely assume that the sections will mostly have some cracking prior to rehabilitation, regardless of the main drivers for the rehabilitation.

Figure 6.3 Crack percentage for maintenance sections identified on the state highways

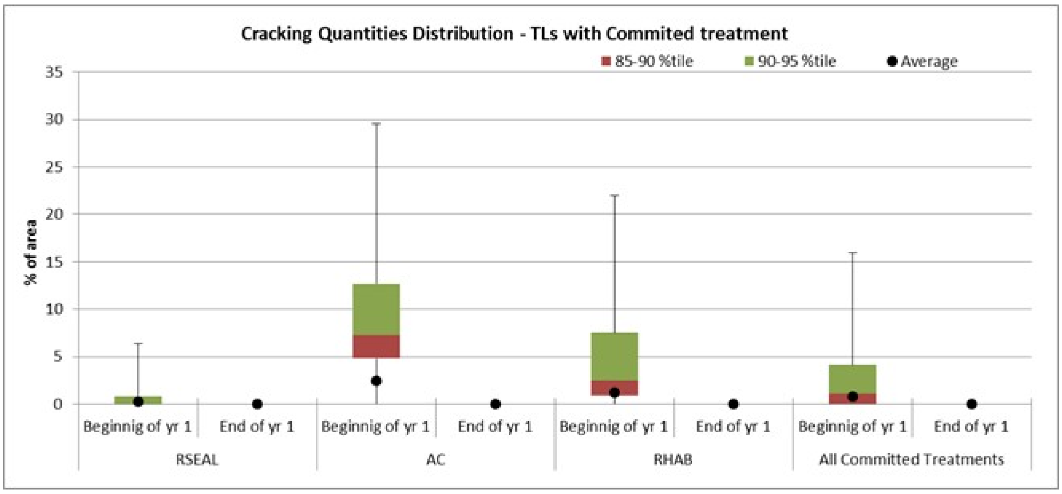
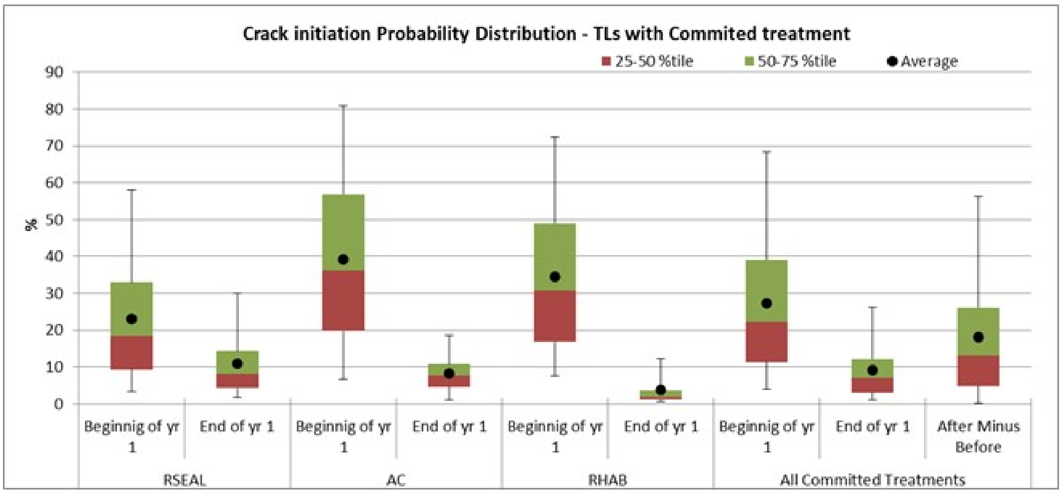


Figure 6.4 Probability of cracking for sections identified for maintenance on the state highways



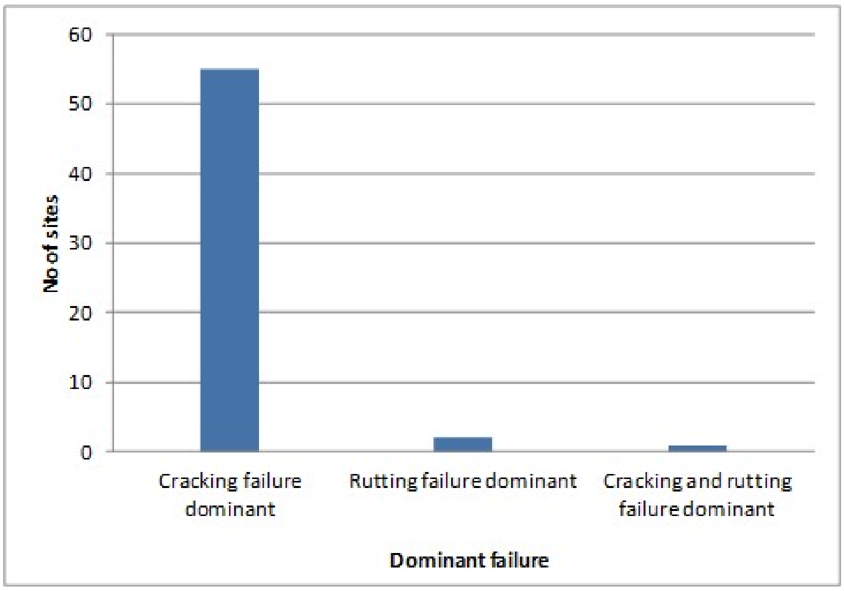
6.4 Investigating dominant pavement failure type – LTPP data

This section presents analysis of LTPP site data to assess the correlations between rutting development, cracking and environmental issues. The objective of the analysis was to identify the reasons for the varying trends of rutting development when other defects, particularly cracking, are present.

6.4.1 Analysis of local authority data

Figure 6.5 shows the number of local authority sites that have rutting and cracking as their dominant pavement failure. This data was collated based on assessments that determined the most dominant failure distresses for each pavement. The total of 86 sites were included in the survey. Of these, 55 sites had cracking as a dominant failure distress, two sites had rutting as a dominant distress, and one site had both cracking and rutting as its dominant failure types.

Figure 6.5 Dominant pavement failure type for local authority LTPP data



Shown in figure 6.6 is the breakdown of the 55 sites that had cracking failure as a dominant failure type with respect to the rutting status of the sites. Of these, 36 sites that were failing due to cracking show an increase in rutting and 14 sites that were failing due to cracking show that rutting had stabilised. On five sites cracking failure was dominant but rutting was decreasing, and on the rest of the sites cracking was not the dominant failure type.

Figure 6.6 Rutting and cracking status of LTPP sites

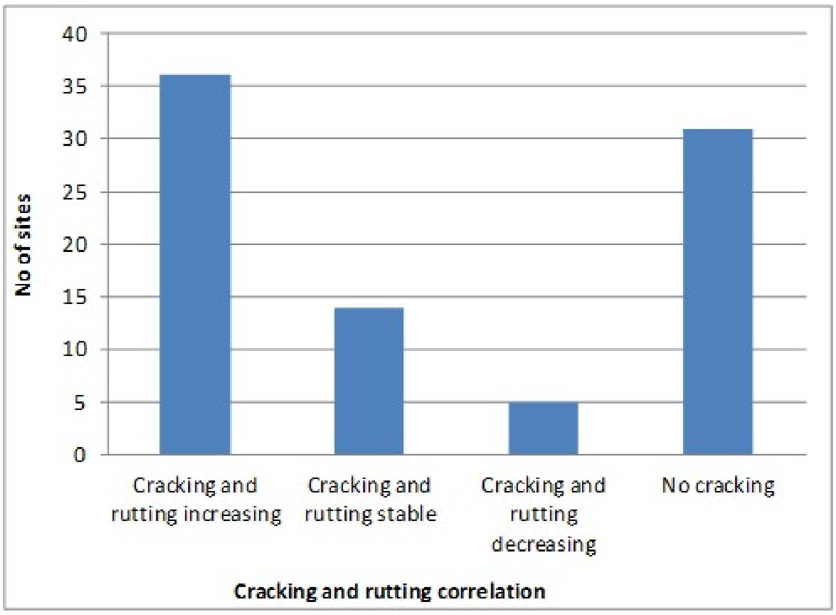
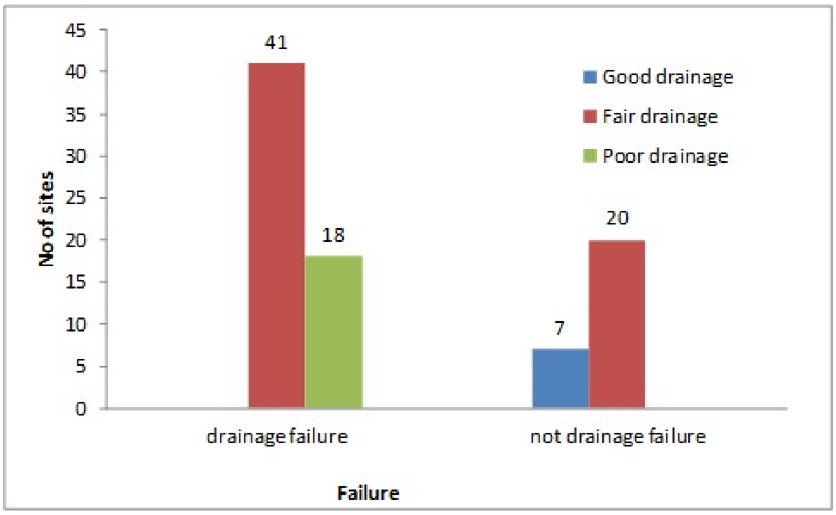


Figure 6.7 shows the drainage status of the sites, with a breakdown showing the sites with drainage as a cause of failure and sites where drainage is not contributing to failure. On all the sites with poor drainage, the failure is related to this. When there is fair drainage, the drainage conditions correspond to the failure of the majority of sites.

Figure 6.7 Drainage related failure with respect to drainage type

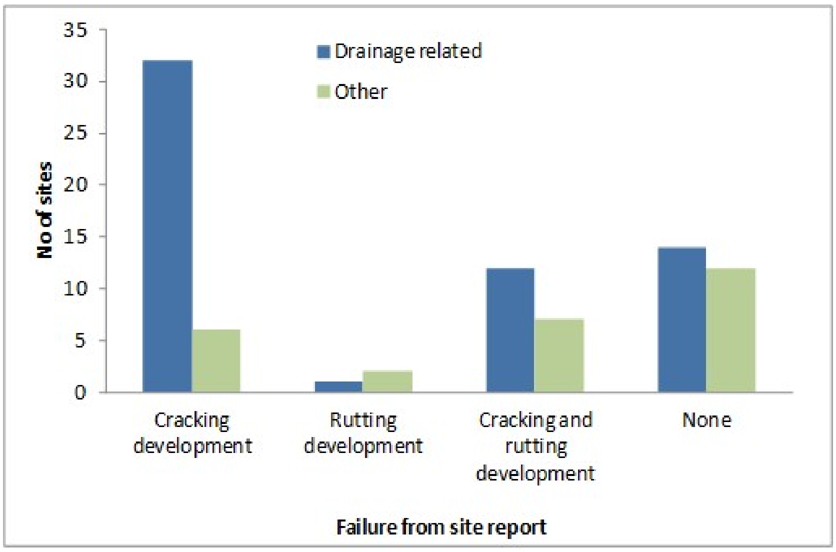


6.4.2 Site report summary and dominant failure type

Figure 6.8 shows a summary of cracking and rutting development as identified from site reports as well as dominant pavement failure type. The site report identifies more rutting development than the dominant failure type data (figure 6.5). Cracking development is observed on 38 sites, rutting development is observed on three sites, and on 19 sites there is both rutting and cracking development.

Out of the 38 sites that had cracking development, 32 sites had drainage-related failure, while on six sites there were no drainage issues. A breakdown of the 19 sites that had both cracking and rutting development showed that drainage-related failure occurred on 12 sites while the rest of sites failed due to other reasons.

Figure 6.8 Cracking and rutting development from site report



6.4.3 Causes of drainage-related failure

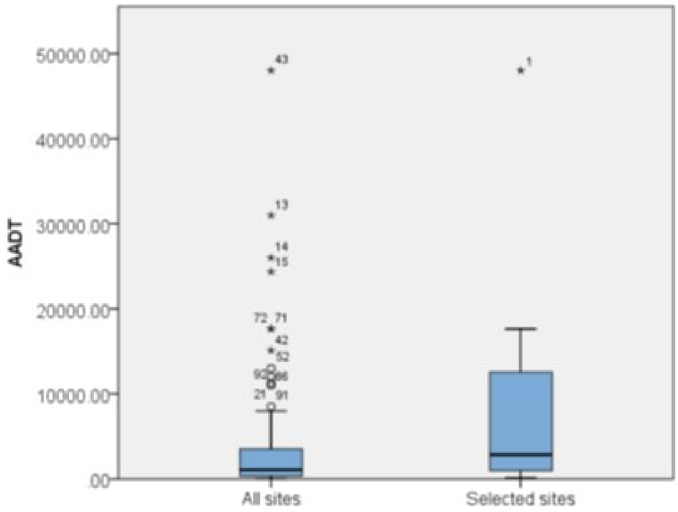
Drainage-related cracking and rutting development

Detailed site information for the sites with drainage-related cracking and rutting is shown in table 6.5. All these sites have a number of other defects that are prominent or cause failure, for example, flushing or potholes are present on most of these sites. All of them are in the medium to high sensitivity categories, and drainage is either poor or fair. The environmental sensitivity of the sites coupled with inadequate drainage appears to be the main problem. Only three of the sites have adequate crossfall, which is likely to contribute to moisture seepage through the cracks. Additionally, the traffic volumes on these sites are also higher than on the whole set of LTPP local authority sites. A comparison of the traffic data is shown in figure 6.9, and as can be seen, the annual average daily traffic (AADT) of these sites is 8,714 vehicles per day (vpd) while the average AADT of the LTPP dataset is 4,190vpd.

Table 6.5 Detailed site information – drainage- related cracking and rutting

Site ID	Drainage	Other deterioration from site notes/dominant failure					AADT	Sensitivity	Cross fall adequate?
		Rough	Flush	Potholes	Patches	Chip loss			
PAP1-S	Poor		x	x		x	7,500	Medium	No
QLD1	Fair		x	x	x		2,154	High	No
QLD4	Fair		x	x	x	x	2,083	High	Yes
SDC3-S	Fair		x		x	x	540	High	Yes
TAU3	Fair		x	x			3,520	Medium	No
TAU4	Fair	x		x			3,520	Medium	No
TCDC1	Poor					x	1,400	Medium	No
TCDC2	Poor	x	x			x	123	Medium	No
WAN3-S	Fair		x	x			450	Medium	No

Figure 6.9 Traffic volume comparison – drainage- related cracking and rutting



Cracking development

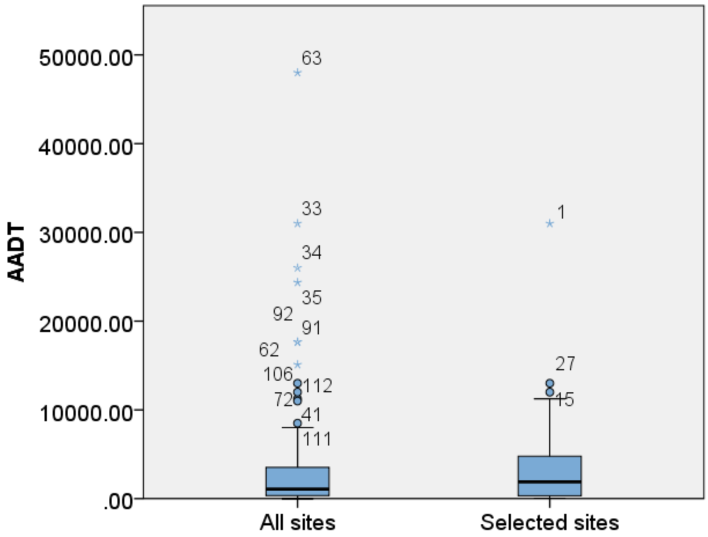
A detailed analysis of the site data for drainage-related cracking sites (32 sites) is shown in table 6.6. Flushing or patches (or both) is present on the majority of sites. All sites are in the medium-to-high sensitivity categories, and drainage is either poor or fair on all sites. The traffic volumes on these sites are similar when compared with the whole set of LTPP local authority sites. A comparison of the traffic data is shown in figure 6.10.

Table 6.6 Detailed site information – cracking only sites

Site ID	Drainage	Other deterioration from site notes/dominant failure					AADT	Sensitivity	Cross fall adequate?
		Rough	Flush	Potholes	Chip loss	Patches			
DUN1	Fair	x					11,250	High	Yes
DUN2-S	Fair		x	x	x		7,600	High	Yes
DUN3-S	Fair	x	x	x	x		3,500	High	No
DUN6	Fair	x	x		x		2,600	High	No
GRE1	Poor	x	x		x	x	1,000	High	No
GRE2-S	Poor	x	x		x	x	300	High	No
GRE3	Poor		x		x	x	180	High	No
GRE4	Poor		x		x	x	1,861	High	No
HUT3-S	Fair	x			x	x	400	Medium	No
MAR1	Fair		x	x	x	x	5,100	Low	Yes
MAR2-S	Poor	x	x		x	x	1,900	Low	No
NPY4-S	Poor		x		x	x	350	Low	No
NPY5	Fair		x	x	x	x	13,000	Low	No
PAP2	Poor		x	x	x	x	4,077	Medium	No
QLD2-S	Fair		x	x		x	2,500	High	Yes
SDC1-S	Fair			x	x	x	300	High	No
SDC5	Poor		x	x			160	High	Yes

Site ID	Drainage	Other deterioration from site notes/dominant failure					AADT	Sensitivity	Cross fall adequate?
		Rough	Flush	Potholes	Chip loss	Patches			
TAS3-S	Fair		x			x	458	Low	No
TCDC3-S	Fair		x		x		50	Medium	No
WAN1-S	Fair		x			x	500	Medium	No
WAN2-S	Fair		x			x	500	Medium	No
WCC1-S	Fair			x		x	4,439	Medium	No
WCC2	Fair		x	x		x	2,811	Medium	No
WCC3-S	Fair	x	x			x	247	Medium	Yes
WEL5-S	Fair		x	x	x	x	1,000	Medium	Yes
WHG1-S	Fair			x			8,500	High	Yes
WHG2	Fair				x		11,000	High	Yes
WTK3	Fair		x			x	42	Low	No
WTK4	Poor	x	x		x	x	187	Low	Yes

Figure 6.10 Traffic data – cracking only sites



6.5 Optimal maintenance intervention – state highway network data

6.5.1 Analysis objectives

The previous section has considered what defects are occurring on the LTPP sections with the intent to establish how rutting (as pavement failure) and cracking (as a surface defect) relate to each other. This section takes this analysis further by considering the state highway network on a network level.

The data that was used originated from the national state highway analysis that provided input into the network outcome contracts. All sections chosen for treatment within the next three years were filtered for the analysis reported in the section. This three-year programme represents the most optimal treatments according to the object function for the optimisation process and the budget constraints.

The objective for this analysis was to establish whether it is possible to determine optimal intervention levels for cracking levels in the context of other pavement failures. The characteristics of the analysis were as follows:

- The analysis was undertaken on constant 100m road sections – therefore the impact of the sections has been removed as a factor influencing the optimisation.
- Consistent rules were applied to all sections and no site-specific considerations were incorporated – this ensures that any site-specific issues that impact on decisions in the field were not considered for this analysis.
- The optimisation object function used maximises the overall pavement condition on a network level. The overall condition is defined by a pavement composite index (PCI) defined as:

Figure 6.11 Composite pavement indices used for optimisation

For Asphalt Pavements:

$$PCI = Max\begin{bmatrix} 0{,}100 - 1.6 * SII - 1.4 * Rutm - 2.7 * IRI - \\ 2.1 * Min(3{,}3 - text) \end{bmatrix}$$

For Non-Asphalt Pavements:

$$PCI = Max\begin{bmatrix} 0{,}100 - 1.6 * SII - 1.4 * Rutm - 2.7 * IRI - \\ 1.7 * Min(5{,}5 - text) \end{bmatrix}$$

Where:

PCI	=	Pavement Condition Index
SII	=	Surface Integrity Index
Rutm	=	Rutting in mm
IRI	=	International Roughness Index (mm/m)
Text	=	Texture measurement in mm

Source: Jooste et al (2008)

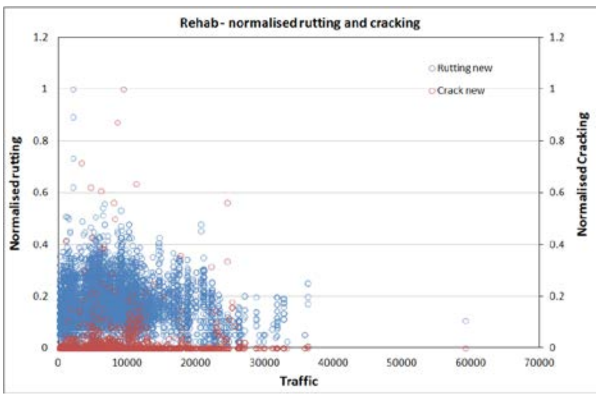
- Routine maintenance costs also play an important component as an intervention point of treatments of the analysis. Yet they were not incorporated into the PCI, thus they will not influence the priority of treatments.

6.5.2 Results

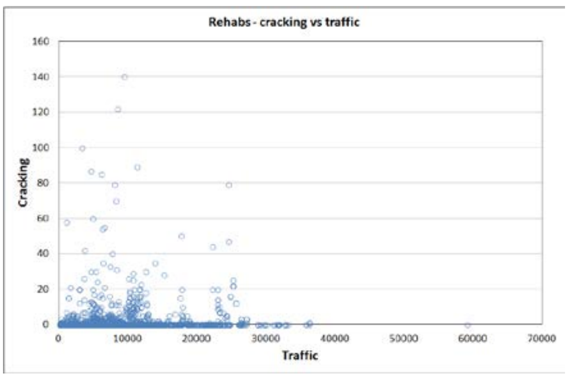
6.5.2.1 Rehabilitation

In order to compare rutting and cracking levels for rehabilitation sites, both values were normalised for their extreme values. Therefore both could be assessed on a scale from 0 to 1 (refer to figure 6.12). The figure on the left hand compares the rutting and cracking levels for rehabilitation sites. The figure on the right contains all the cracking information for the sites that were rehabilitated.

Figure 6.12 Levels of cracking and rutting for rehabilitation sites



Normalised cracking and rutting



Actual cracking

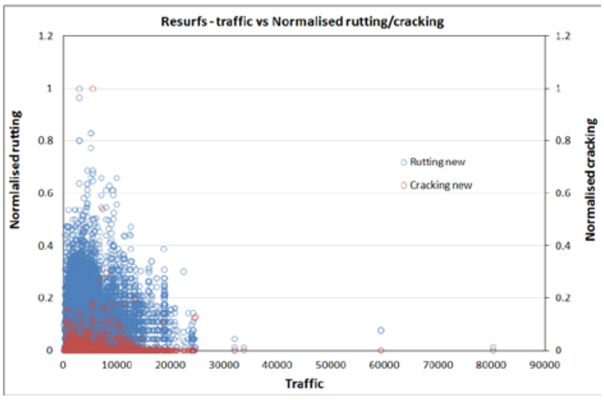
Observations from the figure are:

- It is obvious that rutting is more of a driver for rehabilitation than cracking. This is evident from the trend that the bulk of the normalised rutting is higher than that of cracking.
- Cracking levels are much lower during rehabilitation than crack levels during resurfacing (compare both right-hand plots from figure 6.12 and figure 6.13).
- There were some isolated sections where the cracking was considered as outliers (more than 20% cracking). It is assumed that these sites displayed a significant level of decay.

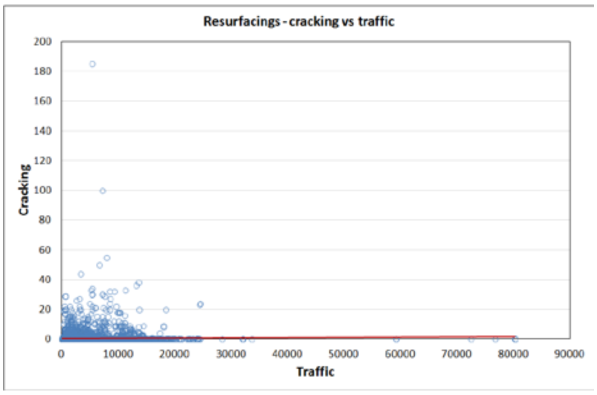
6.5.2.2 Resurfacing

Figure 6.13 shows the same information but only considering the resurfacing sections. Again the left-hand plot shows cracking and rutting according to a normalised scale; the right-hand plot gives the actual cracking values during resurfacing.

Figure 6.13 Level of cracking and rutting for resurfacing sites



Normalised cracking and rutting



Actual cracking

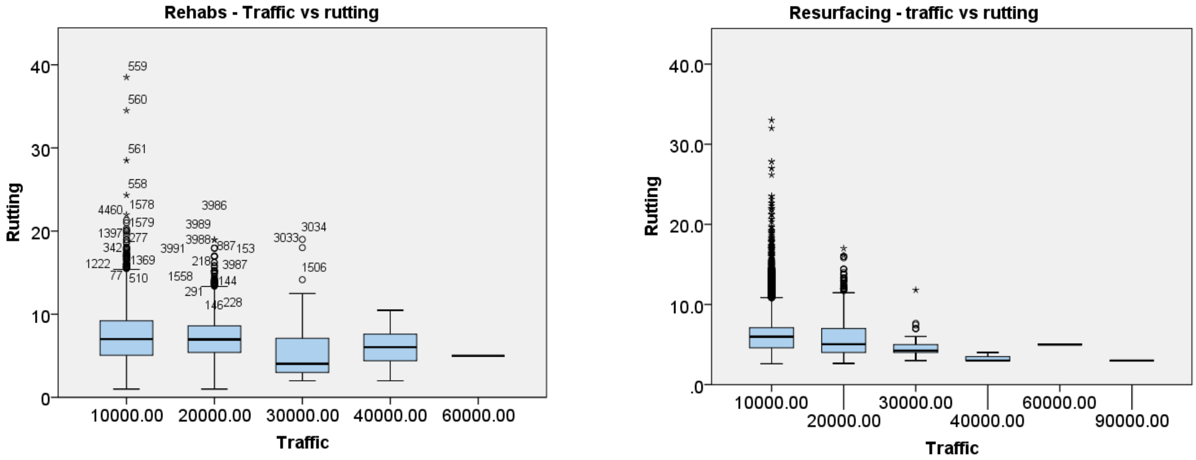
Observations from these figures are:

- The normalised cracking suggests this defect to be much more of a driver for resurfacing treatments. Note that the bulk of resurfacing treatments was undertaken when cracking was approximately 10% or higher.
- It was interesting to note there is still a high level of rutting present, even for the resurfacing sections.
- Less extreme cracking levels are observed for resurfacing than for rehabilitation sites, confirming resurfacing has been applied on early crack stages.

Since it is difficult to compare rutting on the normalised scale, rutting was compared according to absolute values as illustrated in figure 6.14.

The figures confirmed that rehabilitation is undertaken at slightly higher rut levels compared with resurfacing treatments. However, rutting is not necessarily absent during resurfacing. As expected there is nothing special about resurfacing sites, as they are only at an earlier stage of deterioration compared with rehabilitation sections.

Figure 6.14 Rut levels for rehabilitation and resurfacing sections



Rehabilitation rut levels

Resurfacing rut levels

6.6 Discussion of results

The analysis presented in this report has enhanced the current understanding of the deterioration of road pavements, specifically in relation to how cracking develops interactively with other defects. Within this context, the analysis investigated current practices of road maintenance intervention levels as adopted by field engineers and also formed an optimality perspective. An outstanding outcome from this section is reconfirming the complexity of these aspects. The reality is that pavement behaviour is an extremely variable mechanism, where no one pavement would deteriorate according to the same mechanism compared with another pavement. Impacting factors on deterioration, such as traffic loading, the environment, geology, subgrade conditions, drainage and other defects all contribute towards pavement deterioration in varying degrees and significance depending on the specific circumstances of a particular site.

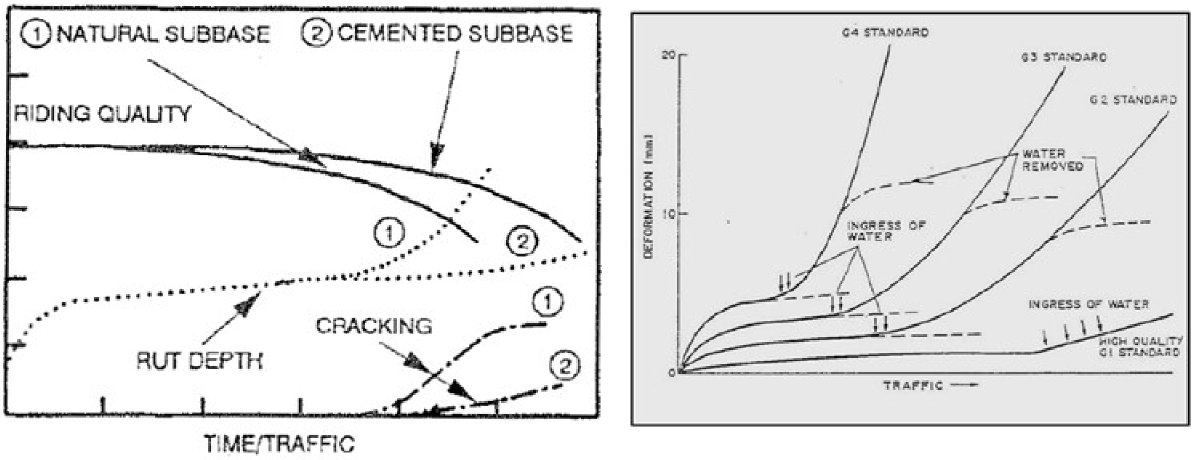
Given the complexity of pavement deterioration, it is natural to accept that the intervention principle for maintenance would be comparably complex. The reality is that it is not possible to come up with simple rules or trigger levels where a treatment would be most optimal for the given defects. Despite these uncertainties, some significant results were obtained from the research as noted in the following sections.

6.6.1 Failure mechanisms of pavements

Cracking remains the most dominant failure mechanisms of pavements in New Zealand. Data from the LTPP programme on both local authority roads and the state highways confirmed the majority of sites showing crack progression either as an isolated defect or in combination with rutting progression. Rutting progression without any cracking was observed on a limited number of sites.

The importance of sufficient drainage has not only been confirmed in this study, in fact, it was proven to be a more important aspect than what has been intuitively believed in the past. Sufficient drainage has a 30% reduced rate of deterioration compared with other road sections in the same environment. From a fundamental pavement behaviour perspective rutting is still the main failure mechanism of granular pavements. Yet, other defects have a significant impact on the progression rate of rutting as illustrated in figure 6.15. The figure shows the impact of water ingress, mostly through cracking of the surface on the acceleration of rutting.

Figure 6.15 Interaction of defects



Source: COLTO (1997)

6.6.2 Intervention approach

Maintenance intervention is never undertaken for a single reason only. Although there are often primary defects of concern, more often than that, maintenance is undertaken when a combination of failures are present. Of particular interest for this research project was the resurfacing as a result of cracking and whether New Zealand practices are indeed the appropriate regime to follow.

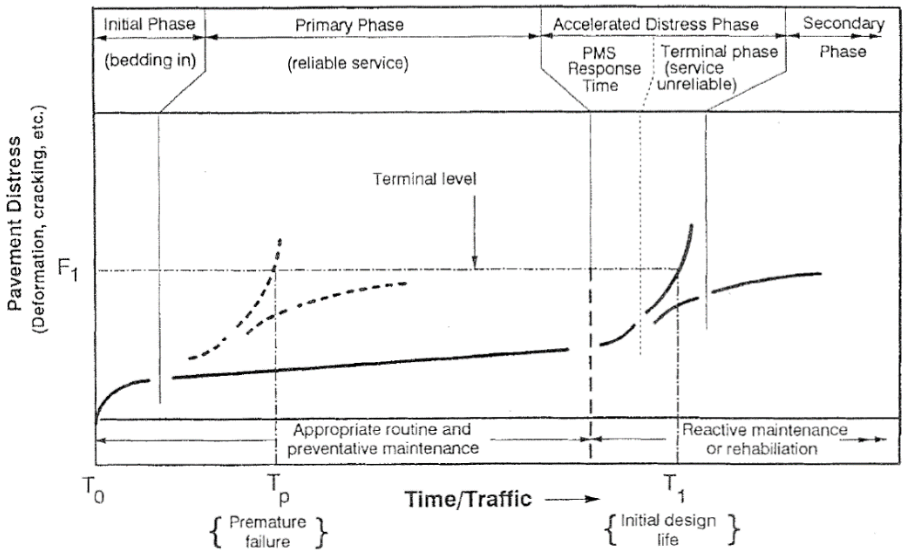
This research has indicated that according to an optimal analysis, there is no specific point of intervention, but rather according to a distribution. What was noticed from this analysis is that resurfacing is mostly undertaken on sections where the cracking is high and rutting levels are low. Rehabilitation is undertaken on sections that have higher rut levels but in comparison lower cracking levels. From this one can infer that resurfacing is undertake on sections where cracking is the dominant failure and rehabilitation where rutting is progressing.

6.6.3 Implication on maintenance practices

Realising that cracking is not the only considerations for deciding on resurfacing treatments, it was striking that current practice resurfaces at lower crack percentages and rehabilitation takes place at higher crack levels. It is well known that scrim and texture is a major driver for resurfacing on the state highway networks. It is therefore recommended that field staff follow a full diagnostic process that considers all defects in context of the field condition in order to make an informed decision on the maintenance requirements.

This research has also shown that the type of treatment is as important a decision as the timing of the treatment. For example, a section that displays rutting in combination with cracking should receive immediate intervention. The window where a resurfacing can still make a difference to the life of a pavement is relatively short (refer to figure 6.16).

Figure 6.16 Optimal intervention timing for pavements



Source: COLTO (1997)

Lastly, the value of sufficient drainage should be recognised by all road agencies. When undertaking life-cycle costing analysis on drainage improvements, it should be taken into consideration that investment into drainage results in a 30% deferral time for pavement works.

7 Conclusions

Although being one of the primary maintenance drivers on New Zealand roads, very little research has been conducted into chipseal cracking. Recent changes in the road sector have resulted in all road authorities questioning the effectiveness and efficiency of maintenance work. In particular, there are some suggestions that practitioners apply resurfacing treatments too often with the motivation of water-proofing surface layers. These pressure points have resulted in the Transport Agency questioning the current knowledge and evidence of the causes and seriousness of road cracking as a main driver of road maintenance.

This preliminary study investigated a number of aspects of the problem and some of the findings are summarised in table 7.1.

Table 7.1 Main findings from the research

Research question	**Causes of cracking:**
Findings	Measurements on laboratory-prepared and chipseal field specimens indicate that multi-layer seals will have fatigue lives in the order of eight times that of typical New Zealand asphalt mixes under the same loading conditions, and that oxidation of bitumen in chipseals is unlikely to be a governing factor in development of fatigue cracking in seals. The long fatigue lives are consistent with the high bitumen content and low initial moduli of the seal specimens compared with asphalt mixes. The long fatigue lives predicted by the results are, however, apparently incompatible with the observation that cracking in seals often develops very early in the seal life. This suggests that cracking in seals is due to very high localised defections caused by weak areas of water saturated basecourse or damage to the seal layer itself from flushing.
Explanation/ meaning of results	This means that the fact a surface shows some cracking is not a reflection of the poor performance of the surfacing, but rather an indication of the performance of everything below the surface, either within the pavement layer or within the multiple seal layers underneath the surface. This finding is consistent with observations on the LTPP sections where cracking occurs much faster on multiple chip surfaces where cracking has occurred in the past, suggesting the cracking is a result of movement underneath the surface exceeding normal deflection levels. Therefore in most cases cracking is a reflection of differential movement below the surface.
Practical implications	Practitioners should pay more attention to understanding and explaining the potential reasons for cracking than just noticing the occurrence of cracking. This will help determine more effectively what the appropriate maintenance intervention should be and how urgent such an intervention is.
Research question	**Crack repair and mitigation techniques**

Findings	Given the lack of guidance for crack repair methods, some guidelines and an outline specification of crack repairs resulting from this research were developed:
	A performance based specification similar to NZ Transport Agency pilot specification P25 for high-friction surfacings is suggested, in which a minimum performance level is set for the duration of a two to three year defects liability period.
	Satisfactory performance would be assessed in terms of:
	• the absence of significant tracking or bleeding
	• the absence of potholes on a repaired crack
	• the percentage of repaired crack length that had failed, defined as:
	  - reopening, spalling or widening of repaired cracks
	  - loss of adhesion of the sealant bandage to the surface
	In addition some basic physical test requirements have been suggested that would be set to exclude obviously unsuitable materials. These requirements would be based on overseas specifications (which many proprietary sealant materials used in New Zealand would already meet).

Explanation/ meaning of results	None
Practical implications	Guidelines and specification should be adopted through contractual arrangements.
Research question	**Crack initiation and growth rates**
Findings	Data from the LTPP sites show that overall, the average number of cracks initiated per site increased approximately linearly from the time of crack initiation. For the three different crack types investigated for both state highways and local authority roads, the average annual increase in crack length for any given crack is approximately half the crack length, so as the crack grows the rate of crack growth in mm/year increases. A brief analysis was carried out for two sites that appeared to show an approximately three-year lag between crack initiation and pothole formation but more extensive analysis is needed before any general conclusions can be drawn.
Explanation/ meaning of results	Research quantifying crack growth of chipseals on the basis of robust data has been limited to this point. The crack growth observed through the LTPP is therefore a breakthrough in itself. The findings contradict earlier assumptions that crack growth undergoes an S-curve type development. These assumptions therefore dictate that initial crack growth to be slower than later on the life of the surface. Also, there is a point when crack development would accelerate if untreated. The findings from this research suggest otherwise. Once cracking starts developing, it can be assumed that: • it will continue to grow • the number of cracks can be expected to grow at a constant rate • cracking will ultimately result into secondary defects such as ravelling and/or potholes.
Practical implications	The previous findings suggested that cracking is not necessarily a performance issue of the chipseal surfacing. Knowing this, one may question the value of addressing the cracking but this finding suggests the opposite. Cracking will keep on growing and result in more serious defects. It is therefore important to do something about the cracking or rather the causes of cracking.
Research question	**Cracking maintenance practices**
Findings	Experienced engineers will always highlight the importance of keeping surfaces watertight in order to ensure good performance from granular pavements. No finding in this research suggests anything different to this philosophy. In fact, the research highlighted the importance of watertight surfaces and good drainage. The results suggest that pavements deteriorated 30% faster with inadequate drainage including surface drainage. The analysis also considered both field programmes and optimal programmes in order to determine some practical guidance for better decision making when considering defects such as cracking and rutting. One of the stand-out observations was that field staff would surface sections at lower crack percentages compared with the rehabilitation sites that normally had much higher crack percentages. The crack percentages for the optimised programme did not differ significantly between rehabilitation and resurfacing treatments. Yet, it was evident that the rehabilitation sections had a combination of cracking and rutting present. The optimal programme was further investigated in order to establish a typical optimal cut-off point where certain treatments were triggered on the basis of defects such as cracking. This could not be established because there are a significant number of factors involved in the optimal timing of treatments. There is also an endless amount of combinations of defects that will determine the optimal timing of treatments. Optimal treatment timing is best determined by software applications specifically developed for this function. It cannot be replaced by simple rules.
Explanation/ meaning of results	Cracking by itself is not sufficient to determine the maintenance requirement of pavements and/or surfaces. It should be viewed within the context of the environment, sufficiency of drainage and the occurrence of other defects. Likewise, there is no magical crack percentage that could be used as a trigger point for intervention; there are too many other factors that must be considered at the same time in order to determine the life-cycle cost aspects for a road section.

Practical implications	It is recommended that field inspections consider the combination of defects in deciding on appropriate treatments rather than considering isolated defects individually. For example a section containing only cracking may benefit from a resurfacing treatment, whereas-as a cracked section that also shows a significant rut rate may be more appropriate for rehabilitation. New Zealand design and rehabilitation guidelines are particularly lacking in suggesting and recommending appropriate diagnostic processes for deciding the appropriate resurfacing or rehabilitation strategies on the basis of an array of condition parameters.

8 Recommendations

This research project was successful in increasing the understanding of the fundamental performance of New Zealand chipsealed roads with respect to cracking. It was also successful in highlighting some of the anomalies of maintenance practices and decision making with respect to dealing with cracked surfaces.

Practical recommendations resulting from the research are:

- Practitioners should pay more attention to the underlying reasons for cracking rather than just observing the mere occurrence of cracking. For example cracking may occur as a result of:
  - multiple surfaces underlying the top surface, which are deforming due to the instability of the layers – often these cracks will co-exist with flushing
  - the pavement is deteriorating or failing and cracking co-occurs with say rutting
  - there may be a drainage issue resulting in failure of subgrade or pavement layers.

  Naturally, the treatment of the cracking in the above mentioned examples may be quite different.
- Cracking should be considered in combination with other condition and/or strength data. The occurrence of cracking is an excellent flag that something is amiss with regards to the pavement or upper layer performance. The only way to make an informed decision on the maintenance needs would be to investigate additional data that would explain the underlying mechanism of the failures:
  - Cracking should receive immediate attention – which does not implicate the consideration of a resurfacing to be the only treatment option. Knowing more about the mechanism of cracking puts more emphasis on routine maintenance activities such as crack sealing and addressing drainage issues. Also, this research has highlighted questions regarding the appropriateness of resurfacing as the most popular treatment for cracking. The real question for maintenance engineers should not be when to consider resurfacing but rather 'when not to consider resurfacing'.
  - New Zealand road engineers are fortunate to have a number of decision tools assisting with the maintenance decisions on site. This research highlighted the incredible complexity of life-cycle considerations taking account of multiple inputs in order to yield the most cost-effective maintenance option. More attention should be paid to the outcome of some of these tools such as dTIMS. The emphasis should therefore not be on sites where the maintenance engineer agrees with modelling results, but rather to learn and understand better what driving factors underpin decisions where the maintenance engineer and the modelling software do not agree on the appropriate treatment.

This research was further effective in highlighting some of the knowledge gaps in our understanding that were outside the scope of this research. Therefore future research should include:

- increasing the understanding of the interaction of multiple defects
- better understanding the water movement through the surface for different surface types, ages, configurations and at different levels of decay
- repeating the research on asphalt surfaces. This research was focused on chip surfaces purely because New Zealand roads mostly consist of chipseal surfacings. However through observing the outcome of peripheral analysis, it was apparent that the cracking is greater on asphalt surfaces and should be further investigated.

Lastly, the research highlighted the need for more diagnostic tools that take account of multiple data inputs in order to decide or eliminate certain treatment types for the combination of certain defects or pavement characteristics.

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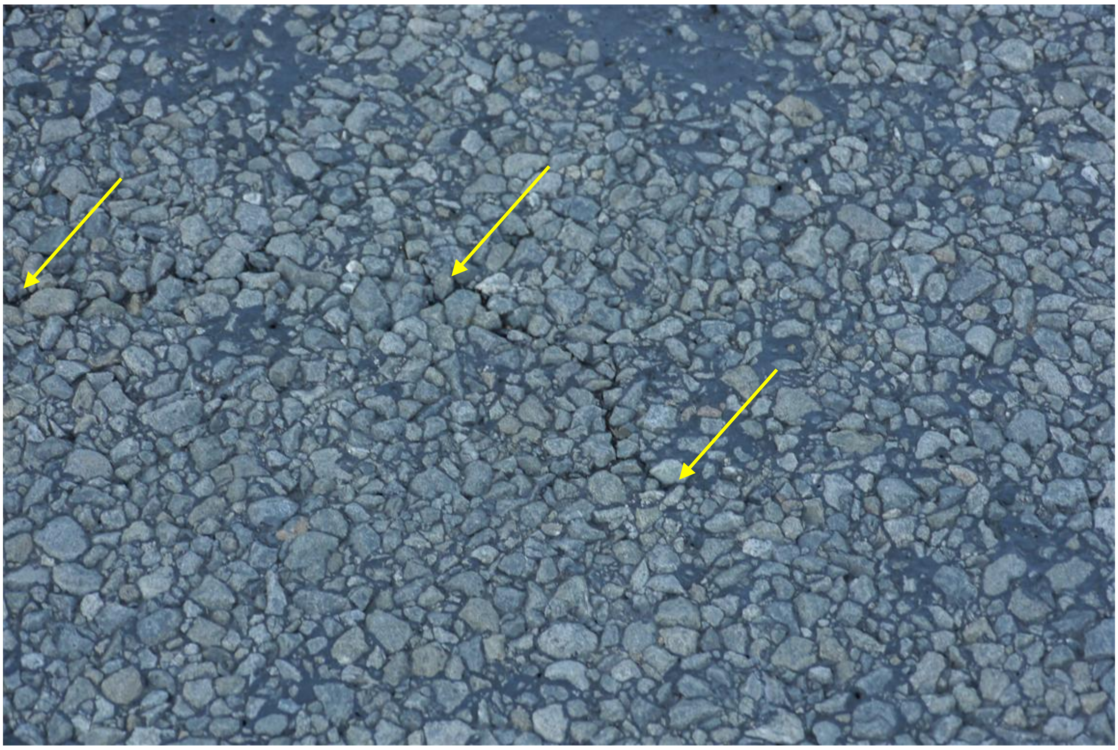
Appendix A: Draft practice guide for the crack repair of chipseals

Cracking occurs in chipseal and asphalt road surfacings for a variety of reasons to do with pavement deflection, joint movements, basecourse shrinkage and bitumen hardening (oxidation). Cracking may allow ingress of water that will result in damage to the pavement layer beneath.

Cracking in road surfacings can be classified broadly as either transverse (across the lane), longitudinal (along the lane) or alligator cracking (usually confined to the wheel paths). Slippage or shoving 'cracks' are also sometimes seen where traffic shear forces have 'torn' the surfacing.

Cracking in chipseals is more difficult to observe than in asphalts due to the surface texture and typically needs to be in the order of several millimetres wide to be easily observable. Cracking is best seen when the surface is drying after rain as water is retained in the cracks.

Figure A.1 Chipseal cracking, longitudinal crack (2–3mm wide) in wheel path



A1.1 Crack repair of chipseals

Crack repair in the present context refers to the repair of specific, individual cracks rather than dig-outs, resealing or applying a large patch of asphalt or seal that overlays both the cracks and areas of intact surfacing alike.

Repair of cracking in seals at an early stage of development should help extend the life of the surfacing by protecting the pavement from water ingress. Large cracks also need to be repaired before resealing. If cracking has advanced to the stage where 'blocks' of the surfacing are moving under traffic then crack repair is unlikely to be successful and will have a very short life. Other forms of repair (dig-outs, patching) are needed in that case.

A1.1.1 Cracks suitable for repair

- Cracks that are free from signs of basecourse fines pumping are best suited for crack sealing. Cracks showing significant amounts of basecourse fines pumping or areas of alligator cracking that demonstrate large amounts of movement are indicative of pavement damage and require more substantial repair (dig out and patching).
- Seals demonstrating large amounts of fine cracking (< 2mm) may be more cost effective to treat by resealing rather than individual crack sealing.
- Cracks in severely flushed surfaces are in general not suitable for crack repair, the flushing itself should be treated.

A1.1.2 Crack sealing methods

Two approaches (with variants) can be used:

- Bandaging: a 3–4 mm thick, 50–100 wide strip of liquid sealant is applied (ie extending well beyond the width of the crack and possibly slightly proud of the seal texture). Tapes and preformed, over-banding strips commonly used overseas on smooth asphalt surfaces, are not recommended because of the high texture of chipseals.
- Routing and filling: the top of the crack is routed out to create a rectangular channel which is filled with a liquid sealant. The ratio of the width of the routed channel to the depth should be about 2–4 to 1 to minimise strains in the sealant due to crack movement. There is limited experience with this method on chipseal surfacings and potential chip loss adjacent to the routed area must be considered.

A1.2 Materials selection

- The sealant must bond to the seal surface and flow sufficiently to provide a good seal around the crack edge to prevent water ingress. This is more important for chipseal surfaces which will have a greater macro-texture and less well defined crack edges than asphalts.
- Simple cold poured bitumen emulsions may be used to fill narrow (<2mm) cracks with little movement. Gritting may be required to prevent bitumen pick-up on tyres.
- Elastomeric polymer modified emulsions or hot applied polymer modified materials are necessary for wider (>2mm) cracks and cracks with movement. These materials have greater resistance to flow when in place and can accommodate larger strains due to crack movement than unmodified bitumen. The material must resist pick-up and tracking by vehicle tyres but remain soft and flexible enough to prevent delamination from the road surface at low temperatures.

A1.3 Method selection

Table A.1 Crack sealing method selection

Crack width	Sealing method	Notes
1–10mm	Bandaging	Cracks wider than about 5mm may result in the sealant flowing into the crack and packing of some of the crack depth (with sand or proprietary materials) may be needed. Avoid filling the full depth of the crack as this will reduce the bond of the sealant and may reduce the life of the repair. The finished bandage material must not be tacky so as to be picked up on vehicle tyres and possibly pulled out of the crack. It must also not be a skid hazard (the amount of bandaging should be limited to not more than 1 lineal metre per square metre). Sanding or application of a small size chip to the surface of the bandage to reduce tack and improve skid resistance may be necessary. Added chip must be heated (>120ºC) to ensure a good bond to polymer modified sealants. Avoid excessive bandage heights above the seal texture (>3mm) as these generate noise under traffic, affect ride quality and unnecessarily expose the bandage to possible damage.
>10mm	Bandaging Routing and filling	Routing of chipseals should be limited to seals on asphalt or with four or more seal layers. It is important to achieve a well-defined cut edge without damage to the surrounding seal, this will depend to some degree on the macro-texture of the seal and chip size). Routing of thin seal layers over granular basecourse should not attempted. The routed crack should be properly cleaned before the sealant is applied. Routing is most practical for straight cracks that may result from underlying asphalt joints. Very wide cracks or joints (>20mm) require packing or filling with a fine asphalt mix.

A1.4 Surface preparation

Cracks and the surface adjacent, should be cleaned of loose debris, lichen etc to allow a good bond of the sealant to the crack faces/surface. Loss of bond is the most common reason for failure of seal crack sealing repairs. Care must be taken to avoid damage to traffic and property from flying debris.

Cleaning is usually accomplished with compressed air but mechanical cleaning (eg wire brushing) may also be necessary. When using compressed air pressures of at least 100psi and air flow of 150Ls-1 is recommended (a leaf blower should not be used for cleaning). Care must be taken to avoid damage to traffic and property from flying debris.

A1.5 Application

- The sealant application temperature and acceptable heating time should be as specified by the manufacturer (do not heat the sealant above this temperature).
- The sealant manufacturer’s instructions should be followed regarding minimum road surface temperatures for application, but should generally be above about 5°C and rising. Early morning operations should be conducted with the road in direct sunlight and in the absence of fog or dew. The road surface must be dry but note that water from recent rainfall will be retained in cracks far longer than on the surface. Drying of cracks before sealing using a hot air lance or gas torch may be

necessary but care should be taken to avoid damaging the surface in that case. For hot applied sealants the presence of excess water is apparent from the formation of small bubbles.

- Dry conditions are less critical for emulsion based sealants, but in any case crack sealing should not be attempted if significant rainfall is imminent (within four to five hours).
- Crack expansion and contraction may occur due to diurnal and seasonal temperature variations. Crack sealing on very hot or very cold days should be avoided as this may result in effectively over or under filling of the crack (when the temperature changes) leading to possible failure of the seal (see figure A.2). This problem is likely to be more significant in regions with greater extremes of summer and winter temperatures (eg Central Otago). For these reasons crack sealing is best carried out in spring and autumn.

A1.6 Repair failure

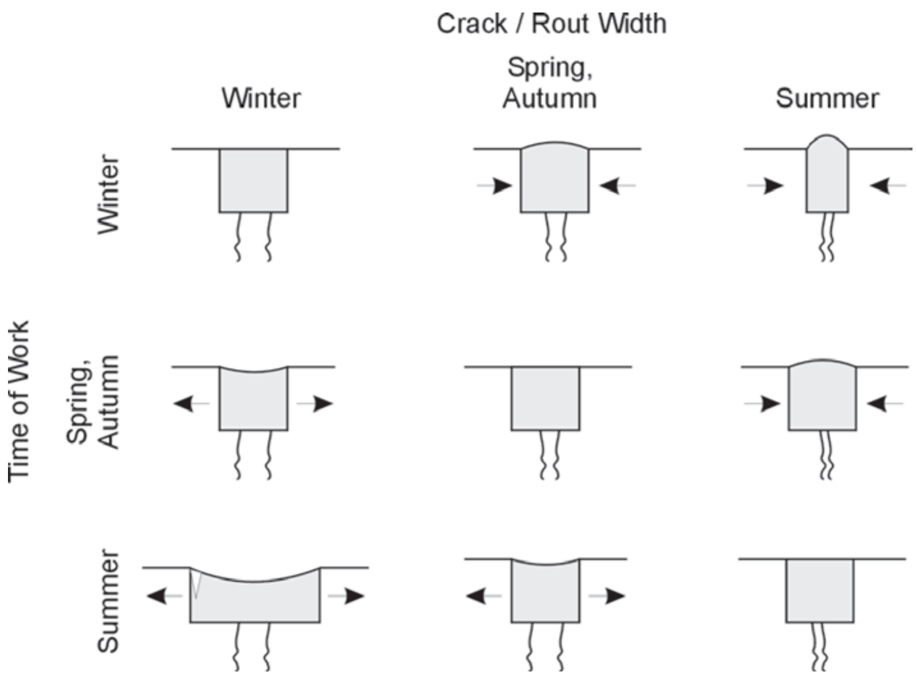
Common reasons for failure of crack sealing repairs are:

- adhesion loss – the sealant does not adhere to the sides of the crack or the adjacent surface
- cohesion loss – the sealant fails in tension by tearing
- incomplete seal.

The crack is not completely sealed, allowing water into the pavement and ultimately leading to pothole formation.

- edge break (spalling) – the edges of the crack break away as a result of poor routing or sawing
- pick-up – the sealant is pulled out of the crack by tyre action
- tracking of the sealant – the sealant has been picked by vehicle tyres or has bled in hot weather.

Figure A.2 Effects of crack sealing at temperature extremes



Source: Masson et al (2003)

A1.7 Satisfactory performance

Satisfactory performance of crack sealing repairs is defined as (within two years of application):

- the absence of significant tracking or bleeding
- the absence of potholes on a repaired crack.

For at least 95% of the repaired crack length:

- no reopening , spalling or widening of repaired cracks
- no loss of adhesion of the sealant bandage to the surface.

Appendix B: Cracking data for the LTPP sites

Table B.1 LTPP site cracking table

		1			2			3			4			5			6			7			8			9			10			11			12			13		
		T	L	A	T	L	A	T	L	A	T	L	A	T	L	A	T	L	A	T	L	A	T	L	A	T	L	A	T	L	A	T	L	A	T	L	A	T	L	A
Local authorities																																								
AKL1	I	Asphalt																																					R	
	D																																							
AKL2-S	I	Asphalt																									R													
	D																																							
AKL3	I							20	2	4	27	4	5	36	6	6	20	8	11	9	1	16		R		Asphalt														
	D							11		6	12		6	25		10	17	1	12	6	1	15																		
BOP1	I							1	1						4			R																						
	D											2		1	4																									
BOP2-S	I																										1									5			3	
	D																																							
BOP3-S	I																							2			1			1			1	1		R				
	D														1			2			4			1			1			3										
DUN1	I	Asphalt																																						
	D																																							
DUN2	I							1			5			1	12					3	2		10	2		5	3		8	1		7	2		13	1		15	1	
	D													1	12			1						2						3			4	1		4		2	13	1
DUN3	I							3	8	1	6	10		8	6		10	6		6	5		8	3			R		1	5		3	2		5	4		11	8	
	D							9	17		11	21	2	15	25	1	13	13	2																			20	16	3
DUN4	I	Asphalt																									R		6	4		18	4		12	1	2	19	10	2
	D																													1			6		3	3		6	8	2
DUN5	I							4			1	4											1			1			2	2		4	5		4	3		2	2	
	D							1				1			1			1															1			1				1
DUN6	I								7	2	1	5	2	12	16	2	4	7	6	11	9	5		R						1			1					5	4	2
	D							4	9	3	2	10	2	12	19	3	15	18	2	13	20	4							4	2	2		3	3	3	3	3	6	5	2
GRE1	I														2						1						R													
	D																																							
GRE2-S	I	No cracking																									R													
	D																																							
GRE3	I																								1		H						R							
	D																			2	2			1																
GRE4	I																										1			R										
	D																																							
GRE5-S	I	No cracking																																						
	D																																							
HAS1-S	I	No cracking																																						
	D																																							
HAS2	I											1	5					2	1		R															1				
	D												7						3																	2				
HUT1	I	Asphalt																																						
	D																																							
HUT2	I	No cracking																																				1		
	D																																					1		
HUT3	I							2	11	1		3			1		1	4		2	4	2		1	2	3	3	1		3	1	1	5	1	1	5	1	4	10	3
	D							1	9	1		4	1	1	3		3	6			8			3	1		9			5	1		6	1	1	6	2	3	8	4
MAR1	I							6	1		6	5		1	13	1	1			4			3		1	2	1		7	3	1	7	4	1	9	4	1	7	3	1
	D							5	4		2	6	1	2	1		1	3		3	4		1	2		4	2	1	5	5	1	5	5	3	6	5	3	2	3	3
MAR2-S	I							1	11	3	2	10	4	3	15	16		10	6		5	14	1	6	15		R								1	1		1	2	
	D							2	7		2	6				1			1	2	1	2	1		2															
MAR3-S	I																																					1	1	
	D										2	1	1											1							1							1		
MAR4-S	I											1																												
	D																																							

MCC1	I	Asphalt																																	
	D																																		
MCC2	I	Asphalt					R																												
	D																																		
MCC3	I	Asphalt																																	
	D																																		
NPE1-S	I									1			1						R																
	D																																		
NPE2-S	I			1			1						1		1	1		1				2						R							
	D			1												1		1	1																
NPE3-S	I																														R				
	D								1			1						3	2					4	2		1	2							
NPY1	I			1			1			1			1			2			2						1			1						1	
	D																																1		
NPY2	I					1	1	1		1	1																								
	D					4	2	1			1																						4	2	1
NPY3	I													R																	2			1	
	D			2		2	5		2	11		1	1	R	1	2			3		1		1	3	5		3	7		3	8		5	9	1
NPY4-S	I		1	4	3	1			3	5		1	2	3	1	4	2	4	3	1	2	1	4												
	D		1	3						4		R		1		2			2	1		2		1	1		1	3					2	6	
NPY5	I		1	4			5		1			3	2		2	3		3	7	2				8	8	1	1	5		2	11	6	5	12	8
	D					2	2	1		1		1	5	5	2	4	2	9	15	5	13	19	2	11	19	5	6	13	2	8	24	2	9	22	10
NPY6	I		1																R																
	D																																		
PAP1-S	I		1	10	1	1	9	1	3	11	4	5	10	3	7	9	6	9	9	7	1	7	1		R										
	D		1	10		1	5		9	8	1	9	7	2	15	5	1	14	9	3		2													
PAP2	I						2			2		1	1		2	1		1	2		2	3		1	2						R				
	D												1			1			4			2			3										
QLD1	I		10	26		11	30	1	28	34	1	13	18	1	23	13	2	19	18	2	20	26	2	21	16	4		H					12	6	R
	D		11	34		10	40	1	38	49	6	9	16	4	21	22	0	16	16		24	24		14	14								2	1	R
QLD2-S	I										1		1			1	1		1	1		1	1		2			6	1	1	4	4			
	D					3	4	1	2	2	1	2	1	1	2		2	3	5	1	3	5	3	3	5	1	6	5	2		6	2		1	
QLD3-S	I									1	1					4			H			R					18			22			24	1	
	D			1	4		1			3	1		3	2	1	1	5										13			17			17		
QLD4	I								1	4			11		7		1		7			H			R					5	10		10	12	1
	D					2	2		3	10		1	12			9	2		12	6										1	8		7	13	3
QLD5	I			11	6		18	1	3	19	5																								
	D			8	3		14	2		14	4																								
QLD6-S	I	No cracking																																	
	D																																		
SDC1-S	I		7	1		9	8		34	10		9	2		12	4		9	3		7	4		8	3			R							
	D		6			4	8		12	13	3	6	1	1	10	5	5	11	8	3	8	5	1	6	5	2									
SDC2-S	I						2		1	2	3		2				3		2	3		2				5			5			6		1	6
	D					2	1		2	5	2		3	2		1	3		2	3		3	4	1	5	5	1	5	6	1	7	3	1	7	4
SDC3-S	I								1			1			1			2	1										R						
	D		1			1			1			1			1												1		R						
SDC4	I		1	2			R								1				1			1			1		1	1		1	2		1	7	
	D																				1								1	3			3	1	1
SDC5	I									1					2				1	1		3			2	1		4			R				
	D			1	2		5			1			1			2	2		6			3		4	6	2		4							
TAS1	I						1			1			1			2		1	3		1	3			4			R			1				
	D																																		
TAS2-S	I	No cracking																																	
	D																																		
TAS3-S	I						1			1	1		1	1					2														1	7	
	D			1			7			8			5									4						2			10			12	
TAS4-S	I			1									1									R													
	D																																		

Chipseal cracking

TAU1	I																	9			13			22	1		18	5						R	
	D																	5	1		3			6	3		9	1	1						
TAU2	I																	4			4	1		6	6		3	3						R	
	D															1	1		7	6	1	6	4		12	6	1	14	3							
TAU3	I																									2			4					R	
	D																	1		2			2			1		1							
TAU4	I																							3	5		6	3	1					R	
	D															2			14	3	1	12	2		15	5	1	25	12							
TAU5	I	No cracking																																	
	D																																		
TAU6	I	No cracking																																	
	D																																		
TCDC1	I	No cracking																													R				
	D																																		
TCDC2	I			1			1			1	3		1	2			2		1	1	1	1	3	1	1	2			1		R				
	D			1							2			1			3		1	2	1		1	1	2	2									
TCDC3	I					1																										1		R	
	D			1			8		1	2	1			1		1			5		1			1	6		1	6		1	6				
WAN1-S	I					1							14						5			7			7			5		3	2		1	4	
	D																																		
WAN2-S	I			5	1	1							2						2			3			1						3			6	
	D																											2			2			4	
WAN3-S	I				5			12						6				1		5			6			3				1		6	4	8	2
	D			1	3	1	6																		5			5	2		3		2	6	
WCC1-S	I				2	2	5	3	2	2	5			8	2		8		2	9		2	8		1	10	1	1	10	2	6	3	5	15	5
	D												2	2		2	2			1			1					3	3		4	1			
WCC2	I			2	1		8	1					5	2	1	5	4	1	3	2	1	3	2	4	3	2	3	3	2	2	6	3	7	7	2
	D			1	2		2	2					2	1		1	2		2	1		1	1	2	2	2	2	2		2	2	2	3	3	3
WCC3-S	I				1			1		2		1			1			3	3		3	2	4	5	6	5	4	5	5	2	1	5	6	14	15
	D						2			3	1		1	2		1	3		1	3			3			3			1			1		5	3
WEL1	I	Asphalt																																	
	D																																		
WEL2	I																																	1	
	D																																	1	
WEL3	I																				4	2		4	2									R	
	D																																		
WEL4-S	I																								2			4					3	5	
	D																																		
WEL5-S	I														1	2		1	3		1			2			2					1	5	6	2
	D		1	3			2			4		1	4						4		3	2	2	3	4	2	3	4	2	1	3	2	4	4	3
WHG1-S	I	Asphalt																																	
	D																																		
WHG2	I	Asphalt																																	
	D																																		
WHG3-S	I																													1					
	D																																		
WHG4-S	I														1			2			5	3		4		2	5	4	3	6	3		8	6	2
	D										1	1					1			1		1		4	8		5	7	1	6	8	1	17	18	3
WHG5-S	I											1	1		1	3		4	2		11	3		13	10		22	9		22	9		17	14	
	D								1			5	1		11	4		3	1		7	1		7	3		22	4		20	3		32	4	
WTK1-S	I											1							1					1			3			2	1		2	1	
	D																														1			1	
WTK3	I			3						6			4						3			4	1		2	1		3	1		6	1		R	
	D																		1			4													
WTK4	I																								6	1	1	7	1				2	3	
	D				1									1							1			1	1		3	4			1			3	

State Highways

CS1	I														R									R			R													
	D											2																		2			3			2			4	
CS2	I			2		1	2		1	2		1	2	2	3	5	2	4	3		3	6		2	5	1	3	5		1	7	2	2	4	5	6	5	9	6	6
	D									5	1	3	1			5			8		1	5			2		1	6	1		7			7		2	3	1	1	6
CS3	I																																							
	D											1	1		2			1	1			1		3	1		1	1			1			1		1	1			
CAL4	I			5			4	R	2	5																				R										
	D			2			2	R		3																														
CAL5	I											R								1	3	2	3	1	2	4	5	1	7	11	1	14	5	1	17	5		19	13	
	D														1			1			1			1			1			2		1	3			2		1	7	
CAL6	I			1			1		1				2			1						1																		
	D																								2			1												
CS7A	I	Asphalt																			R			R																
	D																																							
CS7B	I	Asphalt																			R			R																
	D																																							
CS8A	I	Asphalt																												R										
	D																																							
CS8B	I	Asphalt																												R										
	D																																							
CS11	I	2			3	1		8	2	2	6	4	2	6	4	2	7	3	5	17	3	7	10	5	2	14	H		3	R		8	2	1	2	2	1	2		
	D			1	3			4			9	1		17	1		9	4	4	32		7	14	7		11	H	1	7	R		9	5	1	9			6	1	
CAL12	I																																						R	
	D				1			1			1			1			2			3			5			4	1		4		1	11		1	13		1	15	R	1
CS13A	I																												3			3			9			3	2	
	D																												7			6			17			6		
CAL13B	I																															1			3			4		
	D																																							
CS14	I	1		2			2			1	1		2			H					R					1			4			7		1	18	4		24	8	
	D					3	1	3	1	1	1	3	9		1	H																	3						1	
CS16	I	4		2	4		3	6			5	5	1	5	4	6	7	4	1	6	1	3	12	6	2	8	4	4	5	2	7	2	5	7	4	14	4	10	19	5
	D	11			5			6	2		6	1		9	2	2	5		3	4	1	4	15	1	3	9	3	4	9	1	5	1	5	4	6	12		3	3	
CAL17	I	No cracking																																		R				
	D																																							
CAL18	I																																						R	
	D																							1									1			1				
CAL19	I			1			3			2	1		1						1	1		2									3	3		5	1		2			1
	D			1			3			7	1	1	5			5			7			4	1		1			2			2	1		3	1	1	2		1	1
CS20	I			3		3	1		4	5		R									R				1								1			1			1	
	D			1		1	1		5																															
CS21	I			1		1			3	3	1	5	1	1	4	5			6	3	5	3	1	5	4	4	5	3	1	1	1		H						R	
	D																																							
CS22	I																							1			1				1			1			1	1		1
	D																													1	1		2	1		1		2	1	2
CAL23	I																				1						1	1		1			1	1		4		6	8	
	D																										1			1				1		1			2	
CS24	I	No cracking																																						
	D																																							
CAL25A	I			1												5			1			9		H						R					1	2			8	
	D												4			4			4			6																1		
CAL25B	I																								2			2	3		3		H		10	2			R	
	D						1												1			2						4	6		5									
CS26	I																		1	1		1	2		1	1		3	1	4	3			8		1	10		R	
	D																																	2	1	2				
CAL27A	I																																						1	
	D																																							
CAL27B	I								9															1																
	D		1																					1															1	
CS29	I														1														1		5			6	1		5	1		4
	D																																2	1			1			1
CAL30	I	No cracking							R																															
	D																																							
CS31	I	No cracking																												R										
	D																																							

CS32	I	1		4	2		9	2	3	8	5	12	23		H																									
	D			5	1		5			3	2	3	14																											
CS33	I											1			1																				1			1		
	D																												1			1				1	1	2		
CAL34	I	5	8	1	6	6	1	6	8		10	15		3	13		5	12		5	15	3	6	10			2	R		4		2	4	1	2	4	1	2	6	5
	D	8			3			2			13			2			2	1		2	1		2			1		R	1			1			2			2		
CAL35	I																				1			1								3	7			7		4	10	
	D								2						1		1	3	2	1	2			1	3			1	1			3	2	1	1	3	2		5	4
CS36	I				3	3		2	3			5	2		2	5	2	6	2	7	6	2	11	11	4	5	6	2	4	5	11	5	8	4	6	5	8	6	2	11
	D			6			5	1		2		2	3			4	1	3	1	4	2	3	1	1	4	5		3	2		12	3	6	4	3	1	11			
CAL37A	I																																							
	D	4																																	2			1		
CS37B	I						1																																	
	D																																							
CAL38	I			2																3						3			2	2	1	2	1		3			2		
	D																														2	1			1			2		1
CS39	I			1	2	1			7		1	5			1				2	3			1	1		2		1		1	3		1	3			2	R		1
	D			2					1			2			1			1				1	1	1		1			3	2	1		1	2		5		R		
CS40	I						4										1	2									1		2	1	1		R							
	D						1																							1										
CAL41	I			5																			1	1				1		1					3			2	4	4
	D			2	3			1	3			2			1	2																	1			2			5	
CS42	I						9		16			8						2	1	2	3	1	5	5	5	1	3	11	3	6	10	3	9	9		18	11	1	7	5
	D						3		9			3				1		2	1	3	5		1	7	1	3	9	6	2	6	1	8	11		3	14	1	6	12	10
CAL43	I				2	2		2	6	2		9	3	2	8	3	3	4	6	6	5		7	3	3	7	9	6		H									R	
	D											2			1	3		1	5		1	2		1	4		2	4												
CS44	I								10			7			19			9			14			15			14			12			12			13		1	14	
	D			1		1			3			4			5		1	3			1			5			4			5			4			2			1	
CAL45A	I																																							
	D																																				2			3
CS45B	I			1																																				
	D								1														1			2			1	2		2								
CS46	I			2	1		1		2	4	5	1		2	1	1	2	3		7		1	4	4		2		1	2	1	2	3	3		4	5	1	7	6	2
	D																																1							
CAL48	I																							R											2					
	D																																							
CS49	I			2	3	3	4	2	22		5	6		5	16	2	12	4			6	9	4	11	14	5	13	2	2	1	11		H			R				
	D																			2				3		1	6		3	6	1									
CS50A	I																																							
	D																																						3	
CAL51	I											R																												
	D																																						1	
CAL52A	I			1			1		3			3			2	1	1	4		1	3	2	1	6			R						2			2		1	2	1
	D																																							
CS52B	I			4	1			1				2	1	1	3	3	2	4	2	1	4	3	1	6	2		R		1	3		3	3	2	1	3	3	1	3	3
	D														1									1			2			1										
CAL53	I																													1			1		3	1		2	4	
	D						1	1		1			2			1	2			2	1	4	3			4		1	3	4	2		2	3	4		3	4	2	3
CAl54	I																1			3			2	1		3			2	1	2	4	1	2	11	4	2	34	8	3
	D			1								1			1			1			1			1	1			1	1		1	1		1	1		2	1		1
CS55	I																				1		4	1		1	1			R					2			1		
	D																			3			10	1		4									4	5		11	1	
CS56	I	No cracking																																						
	D																																							
CS57	I										3			3			10			12			12			14			14			24	2	1	2	R				
	D																																							
CAL58	I																																				1			1
	D														1				1			1			1		1	2	3	1			1	1	1		2			
CAl59	I							8	8																			1	2	2	2	1	2	4	2	6	5	4	10	7
	D	2	2		1	3		23	13		7	1		6	3	1	3	3		5	4	1	6	8	1	3	9	3	2	4	1	4	7	1	13	9		24	8	
CS60	I																2			3	1		4	1			R													
	D																																							
CAL61	I	No cracking																																						
	D																																							
CS62	I																							1		1	1		7		R	1	2		6	3		4	17	
	D																							1			1				R									

Note: Sections highlighted in yellow signify either reseal (R) or rehabilitation (H) work.

Site cracking data for sites is analysed in section 5.2.9

Table B.2 Cal12d transverse cracking

Type	Location	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
tcn	67	0	0	0	0	0	0	0	0	0	200	200	200
tcn	57	0	0	0	0	0	0	0	0	0	100	200	100
tcn	51	0	0	0	0	0	0	0	0	400	450	650	650
tcn	49	0	0	0	0	0	0	150	200	450	450	450	250
tcn	48	0	0	0	0	0	100	150	200	200	450	450	250
tcw	42	0	0	250	250	250	250	300	500	400	550	550	400
tcn	23	0	0	0	0	200	250	250	250	350	400	400	200
tcn	21	0	0	0	0	0	0	0	0	200	200	200	200
tcn	12	0	0	0	0	0	0	0	0	0	0	200	200
tcn	9	0	0	0	0	0	0	0	0	0	300	350	150
tcn	5	0	0	0	0	0	0	0	0	0	100	100	100
tcn	2	0	0	0	0	0	0	0	0	0	200	200	400
tcn	0.2	0	0	0	0	0	0	0	0	0	200	200	200

Table B.3 Cal43 longitudinal cracking

Increasing	Locat	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
lwn	2	0	0	0	0	2,900	3,000	3,600	0	0	3,000	0
lin	51	0	0	0	0	0	0	0	0	4,000	0	0
lwn	72	0	0	0	0	0	0	0	0	0	100	0
len	104	0	0	0	0	0	0	0	0	0	3,000	0
len	112	0	0	0	0	0	0	0	0	0	1,000	0
lwn	120	0	0	0	0	4,500	4,000	4,500	3,000	0	4,000	0
lwn	144	0	0	0	3,500	10,000	6,000	9,400	8,600	10,000	10,000	0
agn1	144	0	0	0	0	0	0	0	0	0	300	0
lwn	159	0	0	0	150	0	200	0	400	450	0	0
agn1	159	0	0	0	0	0	0	400	0	0	700	0
lwn	161	0	0	0	400	0	300	0	800	0	4,000	0
agn1	161	0	0	0	0	0	0	1,000	0	1,000	1,000	0
agn1	168	0	0	0	2,900	4,100	0	0	0	0	0	0
tcn	180	0	0	0	0	0	0	400	400	700	1,000	0
lin	215	0	0	0	0	0	0	0	700	0	0	0
agn2	218	0	0	0	1,800	2,100	0	9,000	9,100	9,300	9,500	0
lin	220	0	0	2,400	1,100	0	0	0	0	0	0	0
agn1	230	0	0	0	0	0	0	0	0	0	14,200	0
agn1	233	0	0	0	0	0	0	4,100	0	0	0	0
lin	234	0	0	3,400	3,800	17,100	3,700	0	3,800	0	0	0
tcn	235	0	0	250	300	0	300	0	0	400	0	0
agn2	268	0	0	0	0	0	1,000	1,400	3,800	0	0	0

Increasing	Locat	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
lin	269	0	0	0	700	0	0	0	0	0	0	0
lin	296	0	0	0	4,000	1,300	2,600	0	0	0	0	0
agn1	296	0	0	0	0	1,200	3,000	4,800	0	0	0	0
Decreasing	**Locat**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
lwn	6	0	0	0	0	0	800	0	1,800	0	0	0
lin	25	0	0	0	0	0	1,000	1,300	0	2,200	2,700	0
lwn	120	0	0	0	0	0	0	200	200	300	300	0
tcn	161	0	0	0	0	0	1,000	0	0	0	0	0
lwn	192	0	0	0	0	0	0	600	0	600	1,000	0
lwn	193	0	0	0	0	0	0	600	0	900	1,400	0
lwn	210	0	0	0	0	300	300	900	900	1,300	1,300	0
lwn	211	0	0	0	0	300	300	500	0	0	0	0

Table B.4 AKl3 alligator crack data

Decreasing	Location	2003	2004	2005	2006	2007	2008
lwn	0	0	0	0	33,000	0	0
agn1	21	0	0	24,800	32,000	23,000	0
agn1	29	0	700	21,000	49,500	55,000	0
agn1	87	6,200	6,700	12,400	17,000	20,000	0
tcn	99	0	0	0	1,500	0	0
agn1	108	0	0	0	2,500	2,000	0
agn1	137	77,500	92,500	101,500	114,800	128,500	0
agn1	150	30,500	32,000	40,000	43,000	59,000	0
tcn	180	0	0	0	3,000	0	0
agn1	181	0	0	0	9,000	0	0
tcn	192	0	500	5,000	11,000	0	0
agn1	202	15,800	20,800	32,100	34,000	35,000	0
agn1	264	0	600	4,500	6,000	10,000	0
tcn	265	0	0	600	500	4,000	0
agn1	270	0	1,900	6,300	5,500	12,000	0
agn1	276	0	0	0	0	1,000	0
tcn	285	0	0	1,500	7,000	7,000	0
tcn	295	0	0	600	600	600	0